AGARD-LS-209

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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD LECTURE SERIES 209

Helicopter/Weapon System Integration

(l'Intégration des systèmes d'armes des hélicoptères)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Flight Vehicle Integration Panel and the Consultant and Exchange Programme of AGARD, presented on 19-20 May 1997 in Winchester, UK, and 22-23 May 1997 in Athens, Greece.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

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Helicopter/Weapon System Integration

(AGARD LS-209)

Executive Summary

The last half of the twentieth century has seen the rotorcraft come in to prominence as a combat system. They have proven their worth in all environments and in all domains of conflict. This Lecture Series considers the problems of integrating externally mounted weapons on helicopters. The focus is on aeromechanical and structural aspects, with additional discussion on operational issues.

- The Lecture Series addresses new aspects in the field of helicopter/weapon system integration; it places a strong emphasis on the lessons learned from recent experiences in actual development programs. This publication includes case histories of weapons integration on the AH-64 Apache, the RAH-66 Comanche, the EH-101, and the Tiger. It should be valuable to anyone currently designing or developing rotorcraft, or anyone involved in the integration of weapons systems with rotorcraft.

This Lecture Series, sponsored by the Flight Vehicle Integration Panel of AGARD, has been implemented by the Consultant and Exchange Programme.

L’intégration des systèmes d’armes des hélicoptères
(AGARD LS-209)

Synthèse

La deuxième moitié du vingtième siècle a vu arriver les aéronefs à voilure tournante à un rang proéminent en tant que systèmes de combat. Leurs mérites ont été clairement démontrés dans tout environnement et dans tout domaine de conflit. Ce cycle de conférences examine les problèmes liés à l’intégration en externe des systèmes d’armes montés sur hélicoptère. L’accent est mis sur les aspects aéromécaniques et structurales, avec en outre, un examen des questions opérationnelles.

- Le Cycle de Conférences aborde de nouveaux aspects du domaine de l’intégration hélicoptère/système d’armes sur l’AH-64 Apache, le RAH-66 Comanche, le EH-101 et le Tiger. Il devrait intéresser tous ceux qui sont impliqués dans la conception et le développement des aéronefs à voilure tournante, ainsi que toute personne responsable de l’intégration des systèmes d’armes dans ces appareils.

Ce cycle de conférences est présenté dans le cadre du programme des consultants et des échanges, sous l’égide du Panel de conception intégrée des véhicules aérospatiaux de l’AGARD.

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OVERVIEW

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SUMMARY

The helicopter is fast approaching a half century of service as a weapon system. From humble beginnings after World War II, largely in the roles of observation platforms and search and rescue vehicles, rotorcraft have evolved to a principal in the modern battle scenario. In the war at sea, the helicopter forms an integral part of a task force capable of launching devasting firepower at surface and subsurface targets. In the airland battle, technology has made the helicopter into a tank killer, troop transport and night observation platform. Finally, in the most unlikely arena, air-to-air combat, modern weaponry has shown the helicopter to be effective against even high performance tactical aircraft.

Under ideal circumstances a new helicopter design is being directed towards certain weapon capabilities, making the weapon integration discipline a mature part of the design process. However, the rapid pace of weapons development often leads to airframe modification programs and weapons kits make high-technology weapons subsystems a part of older aircraft. In such cases, the system integration efforts is sometimes reduced to "cut-and-try". At best, such an approach may be inefficient, at worst it may be unsafe.

The Lecture Series considers the range of interface problems that exist where weapon systems are mounted externally on helicopters. The focus is an aeromechanical and structural aspects, and in addition operational issues and special problems are discussed. Based on the excellent work of the AGARD FMP Working Group 15, the Lecture Series intends to address specifically new challenges in this field, with a strong emphasis being placed on the lessons learned form recent experiences in actual development programs.

1. BACKGROUND

In the modern battle scenario helicopters form an integral part of the military forces and are used in a broad variety of missions and tasks. In Figure 1 the main mission tasks of military helicopters are outlined [Ref. 1], including the logistical or transport operations, like

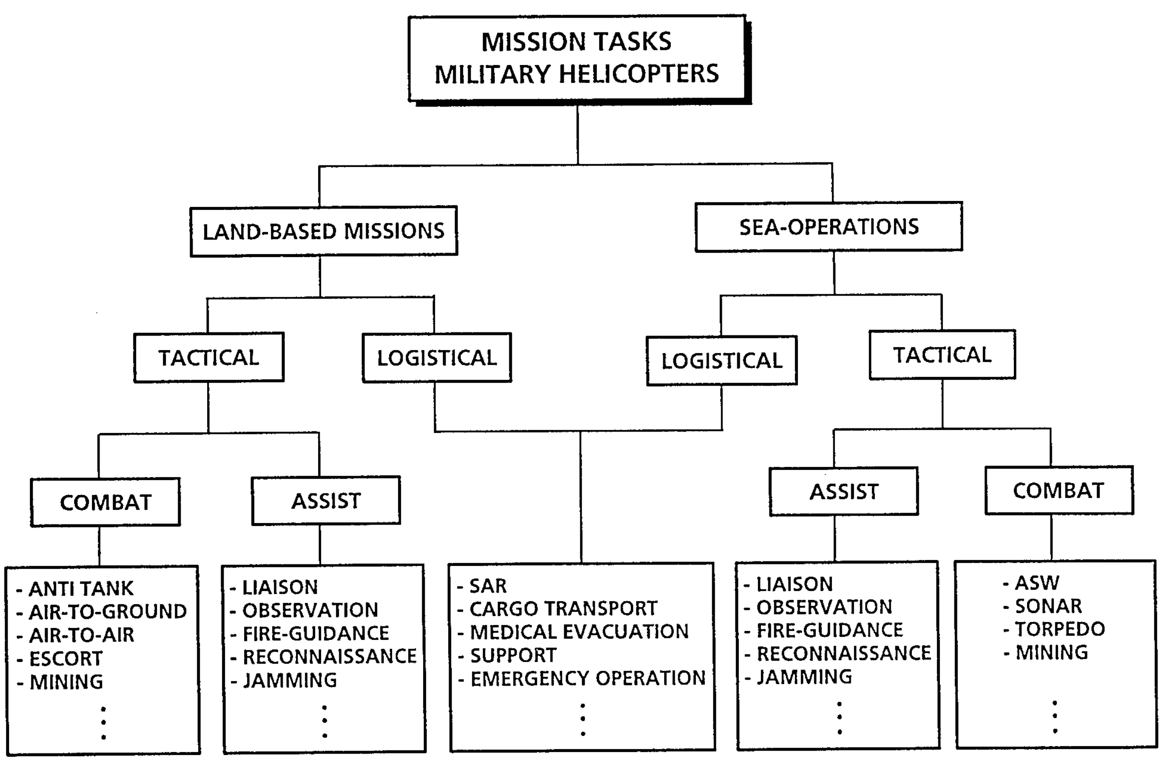

Figure 1: Military helicopter missions

Paper presented at the AGARD FVP Lecture Series on "Helicopter/Weapon System Integration", held in Winchester, UK, 19-20 May 1997; Athens, Greece, 22-23 May 1997, and published in LS-209.

- SAR,
- cargo transport (on board or underslung),
- medical evacuation,
- support,
- emergency operations,

and the tactical operations in the combat and assisting role

- anti tank,
- air-to-ground,
- air-to-air,
- escort,
- mining,
- ASW,

as well as liaison- and observation tasks, fire guidance, jamming etc.

It is obvious that the originally "clean" helicopter needs to be equipped with task oriented installations, in particular with weapon systems for the tactical operations, including guns, rockets and missiles. When arming helicopters with external weapons, it is general practise to equip the aircraft with weapon systems which are already in use on or are derived from land based vehicles, or from fixed-wing aircraft. Three different situations may be considered [Ref. 2]:

- The weapon system is installed on already flying helicopters in the same configuration as used on the land based vehicle or fixed-wing aircraft, simply by bolting-on the limited number of available hard points on the fuselage. This leads to complex weapon carrier structures, and the support structure and the weapon system itself substantially affect the helicopter's performance and handling qualities.
- The weapon carrier for already existing helicopters is redesigned and/or the helicopter is partially modified in order to minimize the penalties of the weapon system integration as much as possible. This approach is often used, in particular for modern helicopters and modern weaponry requiring complicated interfacing between the helicopter and the weapon system.
- Already in the design stage of the helicopter, the configuration is established that minimizes the degradation of the characteristics of the integrated helicopter/weapon system. This may range from the relatively simple solution as the introduction of an aerodynamically effective wing as weapon carrier, to a weapon system aerodynamically integrated in the fuselage.

Depending on the specific solution, the installation of external weapons may cause substantial problems with respect to helicopter performance, handling qualities, structural mechanics, and vibrations and acoustics. In addition, the complicated problems produced by a weapon system inherent set of compatibility conflicts between the host helicopter and the weapon have to be quantified and solved during design, test and evaluation, and operational assessment. This includes solutions for store separation and for special effects caused by weaponization of the helicopter like debris damage, exhaust plume erosion, temperature effects etc.

Some years ago the integration of externally carried weapon systems with military helicopters was studied by the AGARD FMP Working Group 15. As for this Lecture Series the WG 15 efforts were focused on the aeromechanical aspects of the interface problems excluding, for example, the electronic systems integration. The final report of the Working Group (AGARD-AR-247) [Ref. 2] was published in 1990 and is a profound compilation of the helicopters weapons integration experience base at that time. In Appendix I of this report a set of synoptic tables is provided which relates each particular undesirable characteristic to various effects and results and, further, suggests solutions. It was stated that these tables should serve as a guideline for any new helicopter weapons integration venture at the design stage. The information is provided as Tables I and II.

For a specific weapon system integration program the effects discussed above have to be considered in view of the user-defined operational requirements for the overall helicopter/weapon system (Fig. 2). This includes the requirements for the operational flight envelope, for agility, safety/survivability, handling characteristics, and efficiency of the system. The integrated helicopter/weapon system has to demonstrate compliance to these requirements in order to enable the pilot to successfully fulfill the required military mission and to provide satisfactory mission performance.

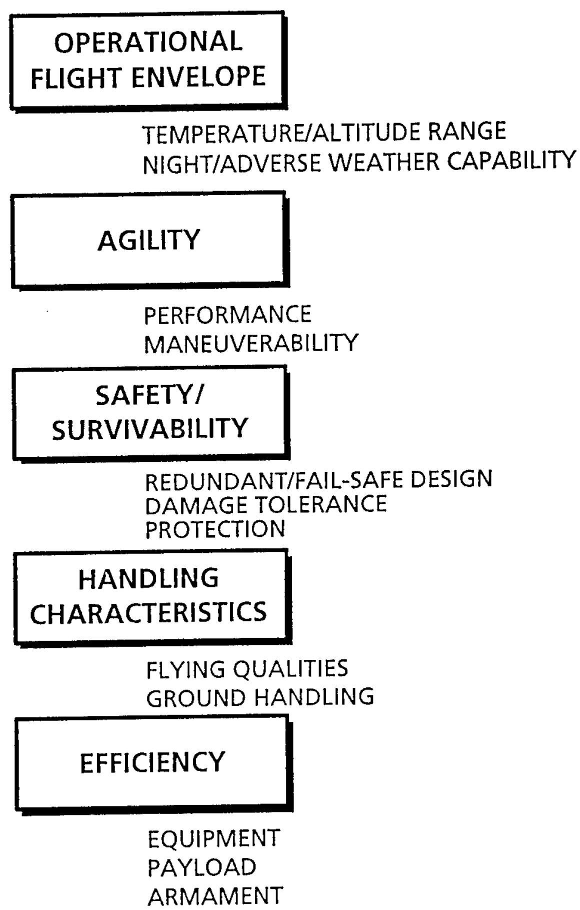

Figure 2: Operational requirements for the helicopter/weapon system

2. OBJECTIVE AND STRUCTURE OF THE LECTURE SERIES

Based on the excellent work of the AGARD Flight Mechanics Panel Working Group 15 and on the related report AGARD-AR-247 [Ref. 2], this Lecture Series intends to address new aspects in the field of helicopter/weapon system integration, with a strong emphasis being placed on the lessons learned from recent experiences in actual development programs.

The lectures start with general presentations on aerodynamics and flight mechanics, structural mechanics, and special effects related to specific weapon categories like droppable stores, forward firing ordnance, articulated weapons, and dispensers. This information deals with modern approaches and procedures in respect to the expected aeromechanical interface problems, and forms the basis for the discussions on the second part of the program, the case histories.

For modern military helicopter systems

- McDonnell Douglas Helicopter Systems: AH-64 Apache,
- Boeing Defense & Space Group, Helicopter Division/ Sikorsky Aircraft Division, UTC: RAH-66 Comanche,
- E.H. Industries, Inc.: EH 101, and
- Eurocopter: Tiger

the specific solutions for the helicopter weapon systems integration problems are presented. These lectures intend to explain more fully the phenomena discussed in the first part, and provide the actual experience base in this field.

It is expected that this extensive information will stimulate the audience to discuss relevant aspects in the round table discussion, and to transform the Lecture Series to some extent to a general workshop.

3. REFERENCES

[1] Schymanietz, K.F.M., "The Impact of Operational Requirements on the Compromise of Desired Features in Rotorcraft Design", in "The Impact of Military Applications on Rotorcraft and V/STOL Aircraft Design", AGARD-CP-313, June 1981, paper 24.

[2] "Integration of Externally Carried Weapon Systems with Military Helicopters", AGARD-AR-247, April 1990.

TABLE I - GUNS (TURRETED, PINTLE AND FIXED)

CHARACTERISTICS	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
GUN RECOIL	COMPLEX TRANSIENT AND REPEATED EXCITATION CHARACTERIZED BY A LARGE NUMBER (20 TO 30) HARMONICS OF THE FIRING RATE WITH DIRECTIVITY PARALLEL TO GUN AXIS. TYPICAL AZIMUTH ELEVATION LIMITS: AZIMUTH: +110° -110° ELEVATION: +15° -60°	o EXCESSIVE DYNAMIC LOADING OF STRUCTURE RESULTING IN REDUCED SERVICE LIFE DUE TO FATIGUE o EXCESSIVE COMPONENT VIBRATION - BLACK BOXES - SIGHTING DEVICES - TRANSPARENCIES o EXCESSIVE CREW VIBRATION o FLIGHT STABILITY MAY BE DEGRADED	o SELECT GUN FIRING RATE TO COINCIDE WITH MINIMUM RESPONSE LEVELS OF AIRFRAME o PROVIDE RECOIL ATTENUATION (ACTIVE OR PASSIVE) o BENCH TEST QUALIFICATION OF COMPONENTS AND SIGHTING DEVICES o LIMIT TURRET ANGLES o ENHANCED STABILITY AUMENTATION	o CONDUCT AIRVEHICLE DYNAMIC RESPONSE TO SIMULATED RECOIL IN 3-AXES: A_Z E_Z 0° 0° 0° -60° 90° 0° o CONDUCT SHAKE TEST WITH SIMULATED RECOIL (3 AXES) o CONDUCT NON-FIRING AND FIRING FLIGHT TESTS
BLAST PRESSURE	HIGH INTENSITY, BROAD BAND, IMPULSIVE EXCITATION	o DAMAGES STRUCTURE DAMAGES ELECTRONICS	o PLACEMENT OF WEAPON RELATIVE TO STRUCTURE o BLAST DIFFUSERS o BLAST SUPPRESSOR o BLANKET STRUCTURE	o CONDUCT PIT FIRING TESTS WITH INSTRUMENTATION TO DEFINE FINAL CONFIGURATION
FLASH	HIGH INTENSITY SHORT DURATION FLASH	o MOMENTARILY "BLINDS" CREW o MOMENTARILY MAKES SIGHTING DEVICES INEFFECTIVE o NIGHT VISION SYSTEMS AFFECTED	o PLACEMENT OF WEAPON RELATIVE TO CREW AND SIGHTING DEVICES o OPTICAL FILTERING	o IN-FLIGHT FIRING TESTS o GROUND AND FLIGHT TESTS
BREACH GASES AND SMOKE	o ACRID FUMES, COLORED SMOKE, RESIDUE o HIGH TEMPERATURES IN VICINITY OF GUN	o OBSCURES VISION OF CREW, OBSCURES VISION THRU SIGHTING DEVICES o FUMES CHOKE CREW o FUMES INGESTED BY ENGINE CAN CAUSE ENGINE SURGE WHICH CAN RESULT IN HIGH DRIVE SYSTEM TRANSIENT LOADING o RESIDUE MAY COAT SIGHT GLASS o IGNITION OF FLAMMABLE MATERIALS	o PLACEMENT OF WEAPON RELATIVE TO CREW, SIGHTING DEVICES, ENGINE INTAKE o ENHANCED GAS DIVERSION AND PURGING	o IN-FLIGHT FIRING TESTS
EJECTION OF CARTRIDGES	o CARTRIDGES MAY EJECT INTO SLIP STREAM AND HIT HORIZONTAL STABILIZER OR TAIL ROTOR	o DAMAGE TO ELEVATOR STRUCTURE OR TAIL ROTOR	o PROVIDE EJECTION CHUTE, INDUCE AERODYNAMIC FLOW	o FLIGHT TEST

GUNS (CONT)

CHARACTERISTICS	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
BARREL TUNING	o NATURAL FREQUENCY OF GUN BARREL CAN BE EXCITED BY MAIN ROTOR HARMONICS OR GUN RECOIL	o EXCESSIVE BARREL RESPONSE WILL INDUCE DISPERSION OF ROUNDS THUS AFFECTING FIRING ACCURACY	o CONDUCT ANALYSIS AND TEST OF GUN BARREL	o ANALYSIS, BENCH TEST, NON-FIRING FLIGHT TEST, FIRING FLIGHT TEST
FIRING TRAJECTORY (TURRETED & PINTLE ONLY)	o ROTOR CLEARANCE	o POTENTIAL DAMAGE TO MAIN ROTOR	o MAINTAIN 3° CLEARANCE CONE	o ANALYSIS, FIRING TESTS
CARTRIDGE TRANSPORT	o HIGH FEED RATES COUPLED WITH LARGE AZIMUTH & ELEVATION ANGLES CAN CAUSE JAMMING	o INOPERATIVE GUN	o DECREASE FIRING RATE o LIMIT TURRET ANGLES o INCREASE FEED CHUTE RADII	o GROUND AND FLIGHT TESTS

TABLE II - EXTERNAL STORES

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
GUNS (POD MOUNTED)	JETTISON AND CAPTIVE CARRIAGE	(TYPICAL OF STORES OF SIMILAR MASS CHARACTERISTICS)			
ROCKETS	LAUNCH TRANSIENT	o SINGLE ROUND INSIGNIFICANT: RIPPLE-FIRE MAY EXCITE STRUCTURAL RESPONSE	o ROCKET POD MAY VIBRATE, INDUCING TIP-OFF ERRORS	o CONTROL FIRING RATE, DETUNE ROCKET POD SUPPORT STRUCTURE	
	INITIAL TRAJECTORY	o ERRATIC TRAJECTORY UPON LAUNCH	o POTENTIAL DAMAGE TO MAIN ROTOR	o PROVIDE 3° HALF-ANGLE CLEARANCE CONE	o STATIC FIRE, FIRING FLIGHT TESTS
	BLAST	o USUALLY INSIGNIFICANT			
	FLASH	o SEE GUNS			
	SMOKE/RESIDUE	o SEE TURRETED GUNS WORST CASE IS FULL SALVO			
ROCKETS	DEBRIS	o USUALLY INSIGNIFICANT			
	DISPENSING	o VARYING MASS CHANGES SUPPORT STRUCTURE NATURAL FREQUENCIES	o RESPONSE TO MAIN ROTOR INDUCED EXCITATIONS MAY BECOME EXCESSIVE IF AMPLITUDE BECOMES EXCESSIVE, DAMAGING LOADS IN SUPPORT STRUCTURE AND AIRFRAME COMPONENTS AND EXCESSIVE CREW, ENGINE AND COMPONENT VIBRATION MAY OCCUR.	o DETUNE SUPPORT STRUCTURE FROM ROTOR HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST, FIRING FLIGHT TEST
	CAPTIVE/CARRIAGE	o STRUCTURAL MODES MAY BE EXCITED BY AND AMPLIFY ROTOR HARMONIC EXCITATION OR GUN RECOIL EXCITATION	o HIGH VIBRATIONS MAY EXCEED MISSILE QUALIFICATION LEVELS; CAUSE DAMAGING LOADS TO SUPPORT STRUCTURE OR TO AIRFRAME COMPONENTS; CAUSE EXCESSIVE VIBRATIONS ON CREW, ENGINE, SIGHTING DEVICES	o DETUNE STRUCTURE FROM ROTOR INDUCED HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST
	HANG-FIRE	o ONE OR MORE MISSILES HANG IN POD	o PRIMARILY A HANDLING QUALITIES CONCERN o HIGH STRUCTURAL LOAD TRANSIENTS o THERMAL EFFECTS	o DESIGN FOR LOADS AND THERMAL PROBLEMS	o DESIGN, ANALYSIS

EXTERNAL STORES (CONT)

TYPE	CHARACTERISTIC	EFFECT	RESULT	TYPICAL SOLUTIONS	APPROACH
MISSILES	CAPTIVE/CARRIAGE	o STRUCTURAL MODES MAY BE EXCITED BY AND AMPLIFY ROTOR HARMONIC EXCITATION OR GUN RECOIL EXCITATION	o HIGH VIBRATIONS MAY EXCEED MISSILE QUALIFICATION LEVELS; CAUSE DAMAGING LOADS TO SUPPORT STRUCTURE OR TO AIRFRAME COMPONENTS; CAUSE EXCESSIVE VIBRATIONS ON CREW, ENGINE, SIGHTING DEVICES	o DETUNE STRUCTURE FROM ROTOR INDUCED HARMONICS	o ANALYSIS, SHAKE TEST, NON-FIRING FLIGHT TEST
	LAUNCH TRANSIENT	o RELEASE OF RETENTION MECHANISM (SHEAR OF PIN) CAUSES IMPULSIVE LOADING	o HIGH TRANSIENT LOADS AND VIBRATIONS RESULT WHICH MAY INDUCE SIGNIFICANT TIP-OFF ERRORS	o DESIGN SUPPORT STRUCTURE TO MINIMIZE MOTIONS AND ACCOMMODATE LOADS	o DESIGN, ANALYSIS FIRING TESTS
	INITIAL TRAJECTORY	o ROTOR CLEARANCE o GROUND CLEARANCE	o SAME AS GUNS o EARLY MISSILE IMPACE	o SAME AS GUNS o OPERATIONAL LIMITATIONS	o SAME AS GUNS
	BLAST PRESSURE	o HIGH INTENSITY, BROAD BAND, IMPULSIVE EXCITATION TRAVELING ALONG THE STRUCTURE	o DAMAGING LOADS ON STRUCTURE; UNLATCHING OF COWLS & DOORS; EXCESSIVE DEFORMATION OF STRUCTURE; EXCESSIVE VIBRATIONS WHICH MAY EXCEED QUAL LEVELS OF ELECTRONIC GEAR	o DESIGN FOR ESTIMATED OVERPRESSURES; CONDUCT PIT FIRING TESTS	o DESIGN, PIT TEST FIRING TESTS
	FLASH	o SEE GUNS			
	SMOKE/RESIDUE	o SEE GUNS	o DUE TO VOLUME OF SMOKE, ENGINE INGESTION IS OF HIGH POTENTIAL; HOT GASES PASSING OVER ELEVATOR AND TAIL ROTOR MAY AFFECT HANDLING QUALITIES AND INDUCE OSCILLATIONS INTO DRIVE SYSTEM		
	HANG FIRE	o SEE ROCKETS			
BOMBS, TORPEDOS, DEPTH CHARGES	HEAVY WEIGHT	o	o HIGH FATIGUE LOADS IN SUPPORTING STRUCTURES	o DETUNING o REDUCED LOADOUT	o DESIGN, ANALYSIS & FLIGHT TESTS
ALL	JETTISON	o ACTIVE JETTISON o COLLISONS o LATERAL C.G. MIGRATION	o LOAD TRANSIENTS o DAMAGE TO A/C o STABILITY & CONTROL PROBLEMS	o DESIGN FOR LOADS o SPECIFIED JETTISON SEQUENCE INTERVAL & FLIGHT REGIME o SYMMETRIC JETTISON o ENHANCED DIRECTIONAL AND LATERAL CONTROL	o DESIGN, ANALYSIS, GROUND & FLIGHT TEST o ANALYSIS AND WING TUNNEL AND FLIGHT TESTS o ANALYSIS AND FLIGHT TESTS

Performance

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1.0 SUMMARY

Power margin is a standard measure of helicopter performance. However, in the competitive market place of today, performance is also an economic measure--cost to operate. Engine technology has significantly reduced fuel consumption and advances in composite technologies have produced lightweight structures. External weapons increase an armed helicopters parasite drag by 40% to 50%. Drag reduction is, therefore, the next largest contribution to fuel savings with figure-of-merit and rotor lift/effective drag ratio improvement the next two important areas.

This paper explores the advances made in rotor blade design technologies following the UH-60 and Apache. The performance of an advanced airfoil rotor design is compared to the UH-60 and other existing helicopters to quantify the advancements. The methodology and analytical tools used to predict the performance of the advanced airfoil rotor is completely described. The resulting rotor system is then used to examine a number of options selected to reduce the drag contribution of external stores.

2.0 PERFORMANCE

Aerodynamics of modern helicopters is the result of many years of work by many distinguished investigators. Technical knowledge and aerodynamic theory has been reasonably well established over the years by analysis, wind tunnel testing, and flight tests.

Since the early fifties, when helicopters were first armed for combat operations in Korea and Algeria, designers recognize the performance limitations of helicopters to be:

- Rotor optimization
- Fuel consumption
- Drag
- Aircraft weight

Armed helicopters used in Vietnam during the sixties had conventional, simple airfoil contours, rectangular blade tips, and metal airframes. With the seventies came low-drag, laminar flow airfoil technology, and the gently ramped leading edge of the Apache and UH-60 main rotor blades. Rotor blade twist was incorporated to produce a more uniform induced velocity distribution across the rotor span increasing hover performance. Higher tip speed was necessary to increase the aircraft's forward flight speed. Sweeping and tapering the rotor tips reduced the significant compressibility losses due to the higher tip speed. This design change also reduces rotor noise.

In 1978, Boeing Helicopters developed and tested the advanced VR12/15 airfoils in the Boeing supersonic wind tunnel located in Seattle, Washington. In 1982, Sikorsky aircraft developed a similar set of advanced airfoils designated the SC2110/SSCA09 sections and evaluated them at the Ohio State University facility. The test results summarized in Figure 1 show that both sets of advanced airfoils offer a significant improvement in maximum lift capability and drag divergence Mach numbers compared to the UH-60/Apache and the CH-47D generation airfoils.

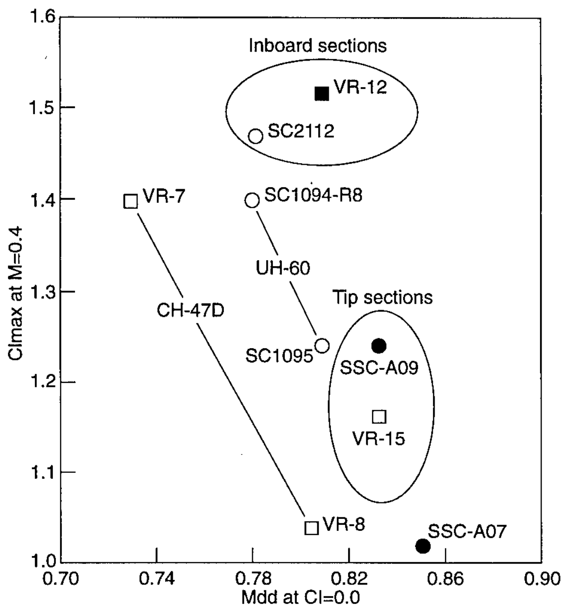


Figure 1. Advanced Airfoils

Advancements in computer-aided design in the eighties now allow designers to optimize the airfoil geometry across the span of the rotor. The advanced airfoil rotor system for this paper uses the Boeing VR-12 for sections inboard of the tip and the Sikorsky SSCA09 for the tip region. The VR-12 has a slight maximum lift and drag divergence advantage over the SC2110. The VR-12 is also currently flying on the Boeing Model 360 demonstrator. The SSCA09 has a small advantage in drag divergence penetration and a lower minimum drag coefficient than the VR-15. Rotor twist is set at 13° to minimize vibration at high speed. Increasing the twist to the UH-60 level would improve vertical rate of climb (VROC), however, this could increase vibratory loads significantly at high speed.

Composite technology advancements provide designers with the option to use more extreme tip shapes and thinner airfoils. Without the fatigue characteristics of composite materials, tip shapes such as rectangular, tapered, or swept tips are the structural and producible solution. Testing, however, consistently shows that taper or sweep by themselves provide only a small improvement

Paper presented at the AGARD FVP Lecture Series on "Helicopter/Weapon System Integration", held in Winchester, UK, 19-20 May 1997; Athens, Greece, 22-23 May 1997, and published in LS-209.

in performance. However, when sweep and taper shapes are combined the improvement is large. Figure 2 illustrates the improvement provided by tip shaping.

Greater utilization of composites in the fabrication of helicopter structures has dramatically reduced airframe weight, making retractable and faired weapons and hub covers (which all tend to increase weight) viable options for drag reduction. The extensive use of composite materials on the Comanche was a dramatic departure from the historical use of metal technology. This dramatic change has resulted in an 18% reduction in the structural weight of the aircraft relative to the UH-60 and the Apache, Figure 3, reference 1. Advances in engine technology have demonstrated substantial decreases in specific fuel consumption, Figure 4. 11% improvement at 700 shp and 6% at 1,200 shp.

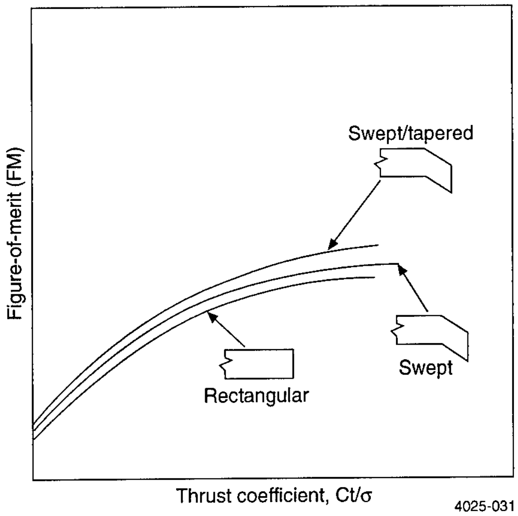


Figure 2. Effect of Tip Configuration on Hover Performance

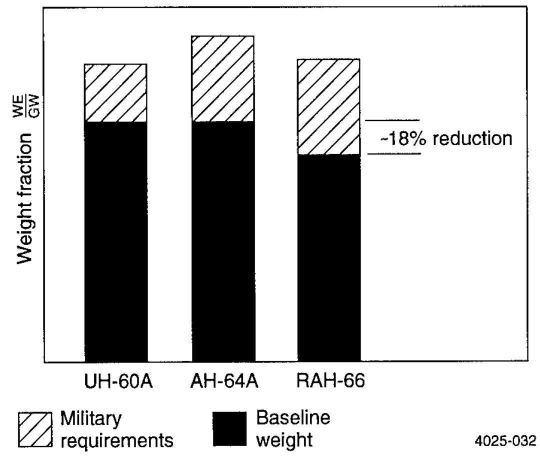


Figure 3. New Materials Offset Militarization Requirements

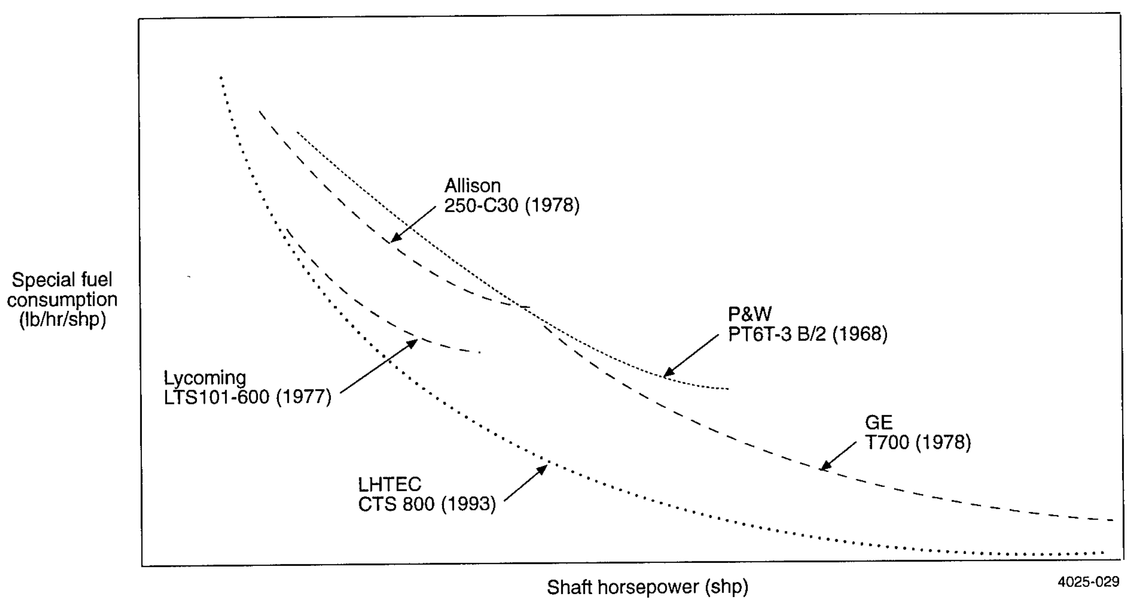


Figure 4. T800 Fuel Consumption is Significantly Better Than Existing Engines

3.0 ROTOR OPTIMIZATION

Rotor performance is typically quantified by two measures: figure-of-merit in hover; and lift-to-drag ratio in forward flight. Rotor figure-of-merit is the relationship of work output (rotor thrust), to energy consumed (rotor shaft torque). The derivation of full-scale figure-of-merit levels from RAH-66 model and full-scale rotor tests are shown in Figure 5. Improvement in figure-of-merit levels is achieved, despite a lower twist relative to the UH-60, through careful tailoring of the tip platform and airfoil geometrics. The tip sweep and taper helps the tip accommodate the preceding blade tip vortex and extends the peak figure-of-merit to higher C_t/sigma levels. Tip vortex generated by the previous blade can induce a very high angle of attack near the tip which might produce a local drag divergence if the tip was not swept.

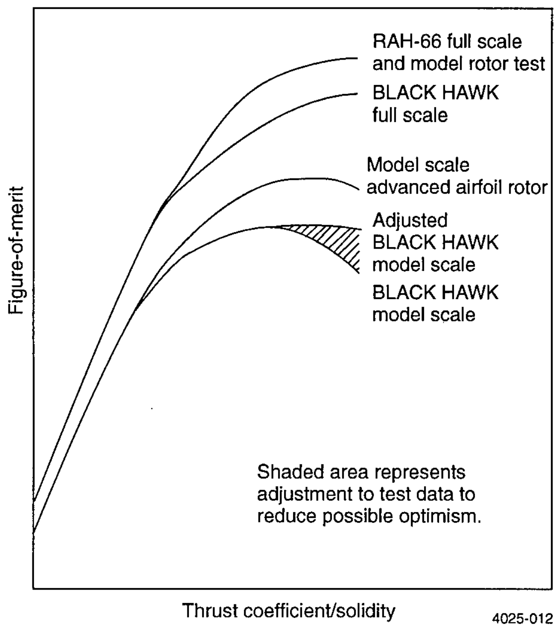


Figure 5. Derivation of Full-Scale Figure-of-Merit from Advanced Airfoil Rotor and BLACK HAWK Test Data

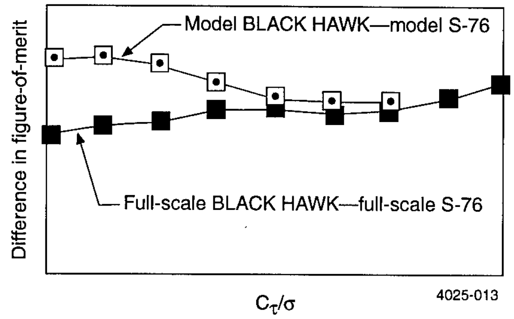


Figure 6. BLACK HAWK and S-76 Buildup of Figure-of-Merit from Model to Full Scale

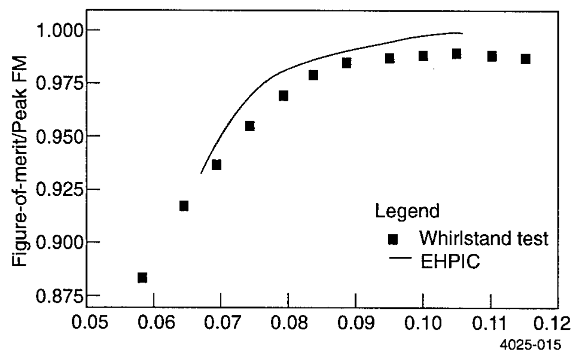


Figure 7. Comparison of EHPIC Prediction With BLACK HAWK Whirlstand Data

Figure 5 does assume that model increments are transferable to full-scale conditions. Experience at Sikorsky has shown that model rotor hover efficiency gains are generally transferable to full-scale conditions prior to the peak figure-of-merit C_t/sigma. Figure 6 shows this by comparing model and full-scale figure-of-merit differences for S-76 and UH-60A rotor systems. At the figure-of-merits of interest, the difference is essentially zero. Figure 7 shows an evaluation of hover performance EHPIC theoretical figure-of-merit predictions for the UH-60A. The UH-60A predictions are compared to whirlstand test results. The predictions are generally in agreement with the test results. EHPIC has been validated against a variety of Sikorsky whirlstand hover data sets, reference 2. The results substantiate the program as one of the premier hover analysis tools available today and is the methodology used in this paper to assess the performance capabilities of the RAH-66 rotor system.

VROC performance can now be quantified as a climb power increment. Data from extensive testing of the YUH-60A and UH-60A aircraft, when normalized to a set of coefficients, establishes a trend that follows predictable physical trends. This dimensionless curve fit in terms of the generalized power variation (GPV) and vertical velocity ratio (VVR), is shown in Figure 8. This curve appropriately accounts for the physics of a rotor in vertical climb, but adjustments obviously need to be made to account for specific design solutions, antitorque system, and system losses. The EHPIC prediction for the UH-60 is also shown in Figure 8. The excellent correlation of EHPIC in vertical climb is comparable to the results shown for hover. Again, demonstrating the capabilities of analytical methods available today to predict rotor, hover, and VROC performance.

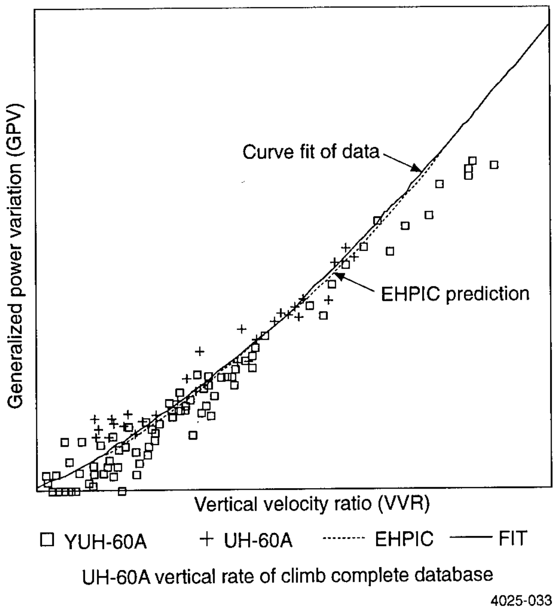


Figure 8. UH-60A Vertical Rate of Climb Correlation

EHPIC computer code, reference 3 and 4, is also used for predicting thrust augmentation when the aircraft is in proximity to the ground, in-ground-effect (IGE) performance. This code uses an image wake and rotor to enforce a "no flow through" condition at the ground plane. The image wake is composed of a series of spiral-vortex filaments generated at the blade tips and carried upward by the image rotor's wake. This concept is used to calculate the upward velocity "induced" at the actual rotor by the image rotor's vortex field. Subtracting this upward velocity from the actual rotor's out-of-ground effect induces downward velocity, producing the in-ground-effect induced velocity distribution. The local effect of the ground-modified velocity at the blade element results in less "induced drag," reducing power requirements. "Profile drag" due to skin friction accounts for only about a third of the total hover power required. The relationship of thrust augmentation to height above the ground, obtained as a result of the rotor system research aircraft (RSRA) testing, is documented in reference 5 and is shown in Figure 9. Predictions for the RSRA thrust augmentation factor using EHPIC is also presented in Figure 9, showing again, good correlation.

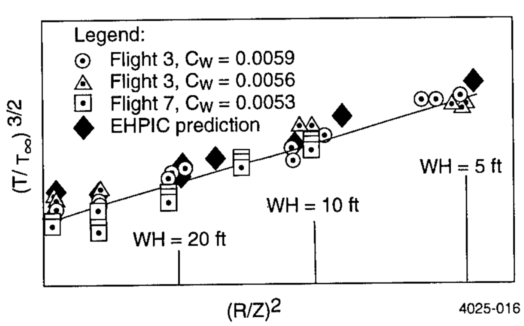


Figure 9. RSRA Hover Thrust Augmentation in Ground Effect

The forward flight data bank (FFDB) program, reference 6, is the methodology used at Sikorsky Aircraft to "map" rotor performance which is determined from wind tunnel tests. The map is corrected for Reynolds number differences relative to the full-scale rotor. As described in reference 7, test data for numerous model and full-scale rotors show that the average rotor minimum drag coefficient, derived from hover data at zero thrust, decreases with increasing Reynolds number (R_e) according to the following relationship.

$$C_d \text{ profile} = \frac{K}{{R_e}^{1/5}}$$

Where K is a function of the rotor airfoil section. Applying this adjustment to the forward flight profile power, gives the following incremental profile power scaling factor:

$$\Delta C_{P_0} = C_{d_{0ms}} \frac{\sigma Q}{8}\left[\left(\frac{R_{e_{ms}}}{R_{e_{fs}}}\right)^{1/5} - 1\right](1 + 4.65\mu^2)$$

In the equation above, σQ is the torque weighted solidity and $C_{d_{0ms}}$ is the average model minimum drag coefficient derived from model hover testing. For thrust levels up to stall inception, this scaling approach has been used successfully to predict full-scale CH-47D performance as described in reference 7 and illustrated in Figure 10.

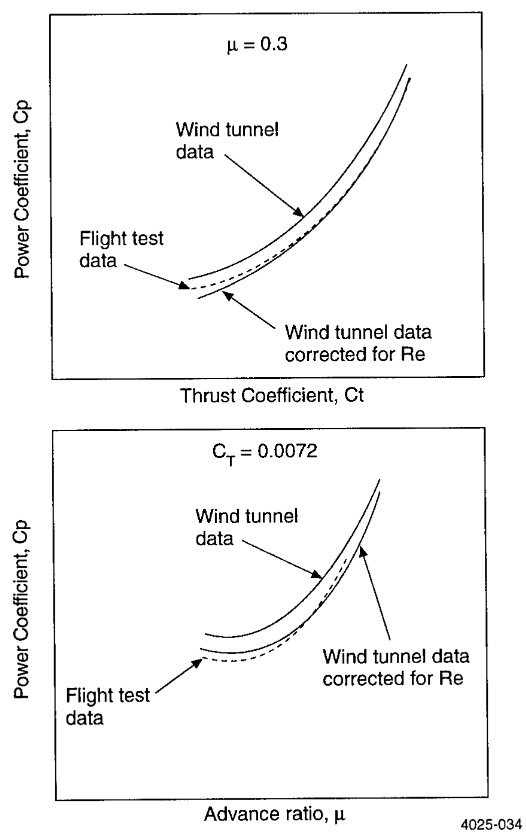


Figure 10. Reynolds Number Correction Applied to CH-47D Level-Flight Power Required

The comparison of UH-60 model and full-scale performance at thrust coefficients above stall inception, have shown that power requirements increase more rapidly with increasing thrust on the model scale rotor than on the corresponding full-scale rotor. To match the UH-60 full-scale test data, additional stall factors must be added to the basic ΔC_{po} Reynolds number correction. The stall factor $(\Delta C_p/\sigma)_s$ based on UH-60 data is shown in Figure 11.

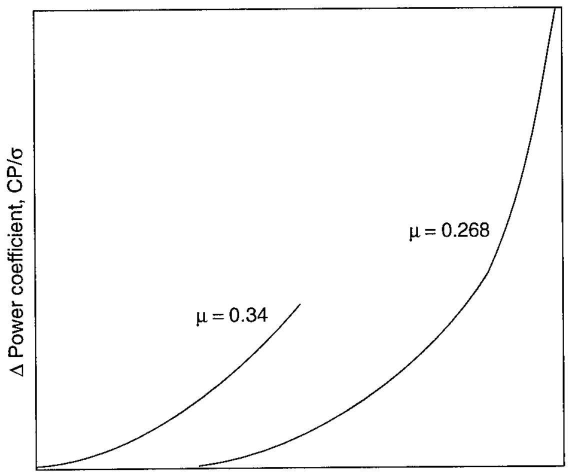


Figure 11. Additional Power Required Scaling Factor at High-Thrust Coefficients

These two factors, ΔC_{po} and $(\Delta C_p/\sigma)_s$, are applied to scale model data to estimate full-scale forward flight performance.

The mapping procedure uses the rotor test data at a specific test condition, and adjusts the FFDB energy-type rotor model to reproduce test trends. The FFDB model can then be used to reproduce test results at the test conditions, and to interpolate the results to other specified combinations of gross weight, advanced ratio, and ambient conditions that were not tested. Figure 12 shows the correlation obtained between the test data and FFDB for the 1/3.5 scale model test prior to the Reynolds number correction.

The FFDB trending of the 1/3.5 scale test data is then corrected for Reynolds number effects on lift and drag, and extended in the high-lift region as previously described. The scale-corrected isolated main rotor data is in general agreement with analytical predictions as shown in Figure 13. Generalized rotor performance (GRP) program, reference 8, is the analytical tool used to make the predictions compared to test data in L/De versus advanced ratio format in Figure 13. Figure 13 shows close agreement between prediction and test, especially at the design point, even though removal of parasite power in the L/De calculation tends to magnify the differences between test and prediction. De is calculated as follows:

$$\text{Equivalent drag, De (kg)} = \frac{198\ P(\text{kw})}{V(\text{kn})} - D(\text{kg})$$

D = drag P = power V = velocity

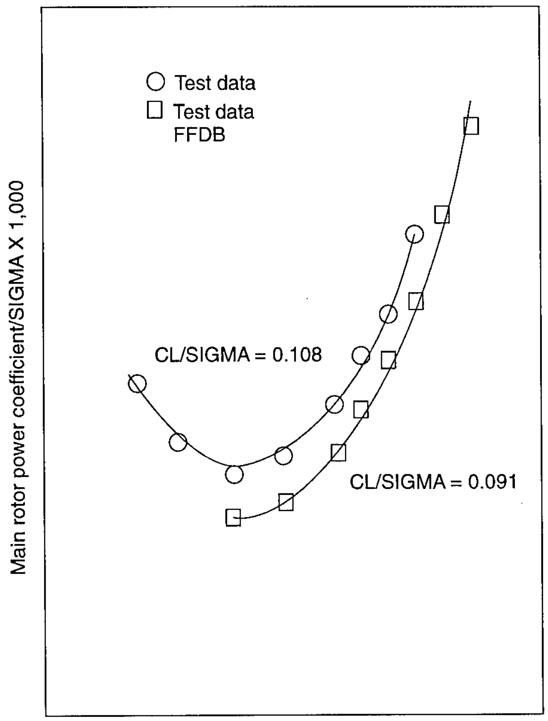


Figure 12. Forward-Flight Correlation 1/3.5-Scale Test vs FFDB Model Scale Reynolds Number

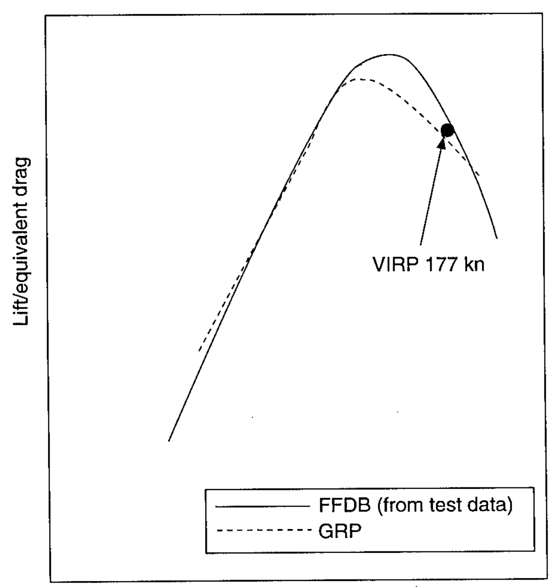


Figure 13. Isolated Main Rotor Forward-Flight Performance, Comparison of Theory and Corrected Test Data

Projected full-scale RAH-66 foward-flight performance, based on the previously described model rotor performance scale-up proceedures, is shown in Figure 14. The figure shows a 15% improvement in rotor lift/effective drag ratio compared to the UH-60A rotor system.

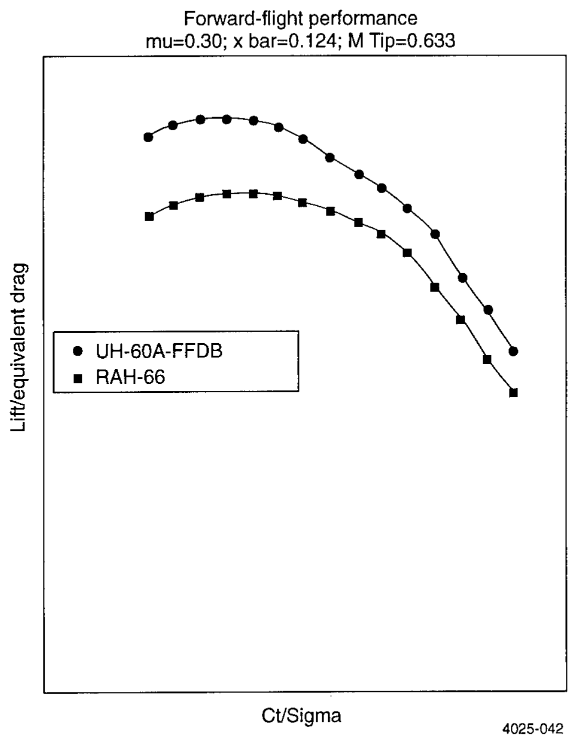


Figure 14. L/De Comparison, UH-60A Versus Advanced Airfoil Rotor System

4.0 DRAG

Sikorsky's standard method used for download predictions is a strip analysis tied to the circulation coupled hover analysis program (CCHAP), reference 9. CCHAP has been correlated with a large number of rotor systems and is used to provide rotor downwash velocities at the fuselage, as a function of radial and vertical position relative to the rotor disk. An example of this correlation, from reference 10, is shown in Figure 15. Use of this program provides a convenient and accurate method of adjusting the downwash velocities for gross-weight variations.

The net lift of an aircraft is determined by several factors including:

- Rotor lift
- Exhaust
- Antitorque system

The interaction between rotor and fuselage can be a major factor and should be accounted for when examining the influence of external weapons. Download and thrust recovery, due to the fuselage acting as a partial ground plane, combine to give the net vertical drag as follows:

$$D_V = \frac{D - T_{recovery}}{T_{main\ rotor}} - D$$

where

D_V = net vertical drag

D = total drag force (kg)

$T_{recovery}$ = thrust recovery (kg)

$T_{main\ rotor}$ = main rotor thrust (kg)

A thrust recovery trend based on the Boeing Model 360 and the UH-60A scale rotor/airframe interaction testing is shown in Figure 16. Without external weapons, an armed helicopter download thrust would be in the 5% range, and about 9% with external weapons resulting in 1.25% to 2.25% thrust recovery, as shown in Figure 16.

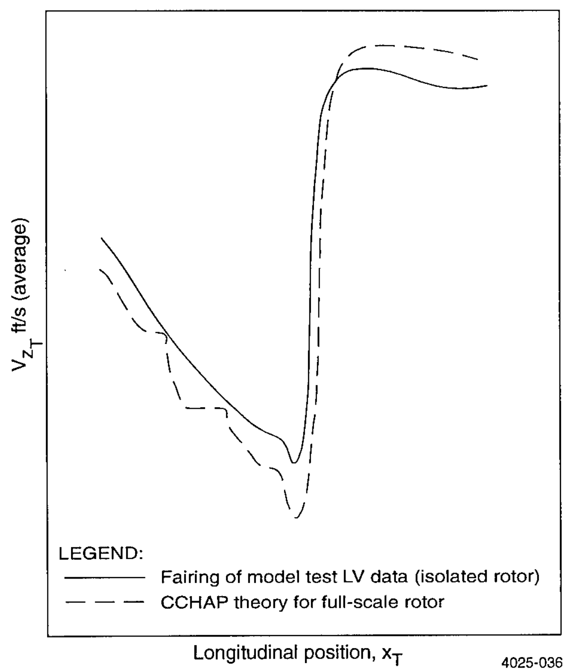


Figure 15. Comparison of Measured and Theoretical Downwash Velocity for AH-1G Rotor

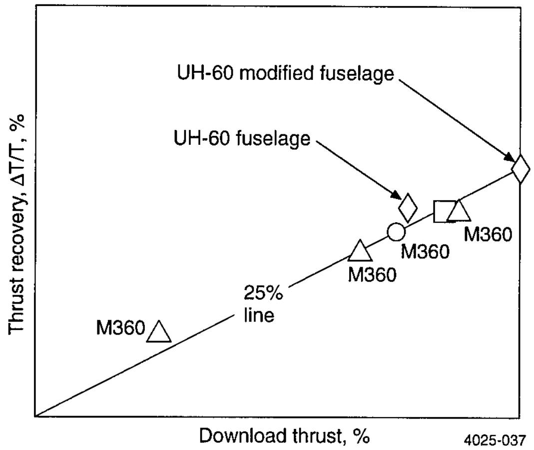


Figure 16. Main Rotor Thrust Recovery Trend

Figure 17 shows the strip analysis for an armed helicopter with external stores. The external stores support system produces 61.35 kg (135 lb) of vertical drag; this is equivalent payload which is important to an existing helicopter, however, for a new design hover theory, reference 11, states the following:

$$FM = \frac{1}{\sqrt{2}} \frac{T^{3/2}}{HpR\pi}$$

or

$$R \times Hp = \frac{1}{FM\sqrt{2\pi\rho}} T^{2/3} \approx (GW)^{3/2}$$

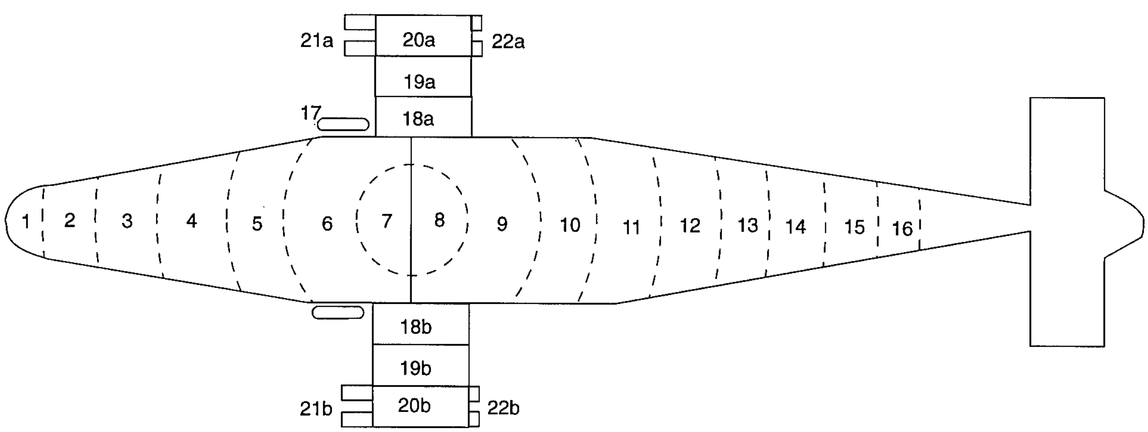
or

$$GW \approx [R \times Hp]^{2/3}$$

where

FM = Figure of merit
GW = Gross weight
R = Rotor radius
Hp = Rotor power

Figure 18, reference 12, shows this relationship in terms of engine power and agrees with the conclusion that a 61.35-kg (135-lb) equivalent increase in gross weight would require a 1.5% increase in rotor diameter, or a 1.5% increase in power. Typically, other operational requirements (such as maneuverability) sizes an armed helicopter's rotor diameter resulting in low disk loading which places the hover condition on the figure-of-merit curve, that favors increasing power to regain performance.



Element	X/R	H/R	C_D	V factor	Area m^2	Velocity, m/s	Dynamic pressure, Pa	Drag, N	Drag, kg
18	0.198	-0.256	1.150	1.000	1.414	15.54	134.4	218.5	22.28
19	0.304	-0.256	1.150	1.000	0.707	20.06	223.9	182.1	18.56
20	0.357	-0.256	0.850	1.000	0.707	20.22	227.5	136.7	13.94
21	0.341	-0.303	1.000	1.000	0.117	21.35	253.7	29.7	3.03
22	0.346	-0.303	1.000	1.000	0.117	23.10	297.0	34.7	3.54

Note: Thrust recovery = 2.65%

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Figure 17. Vertical Drag Strip Analysis

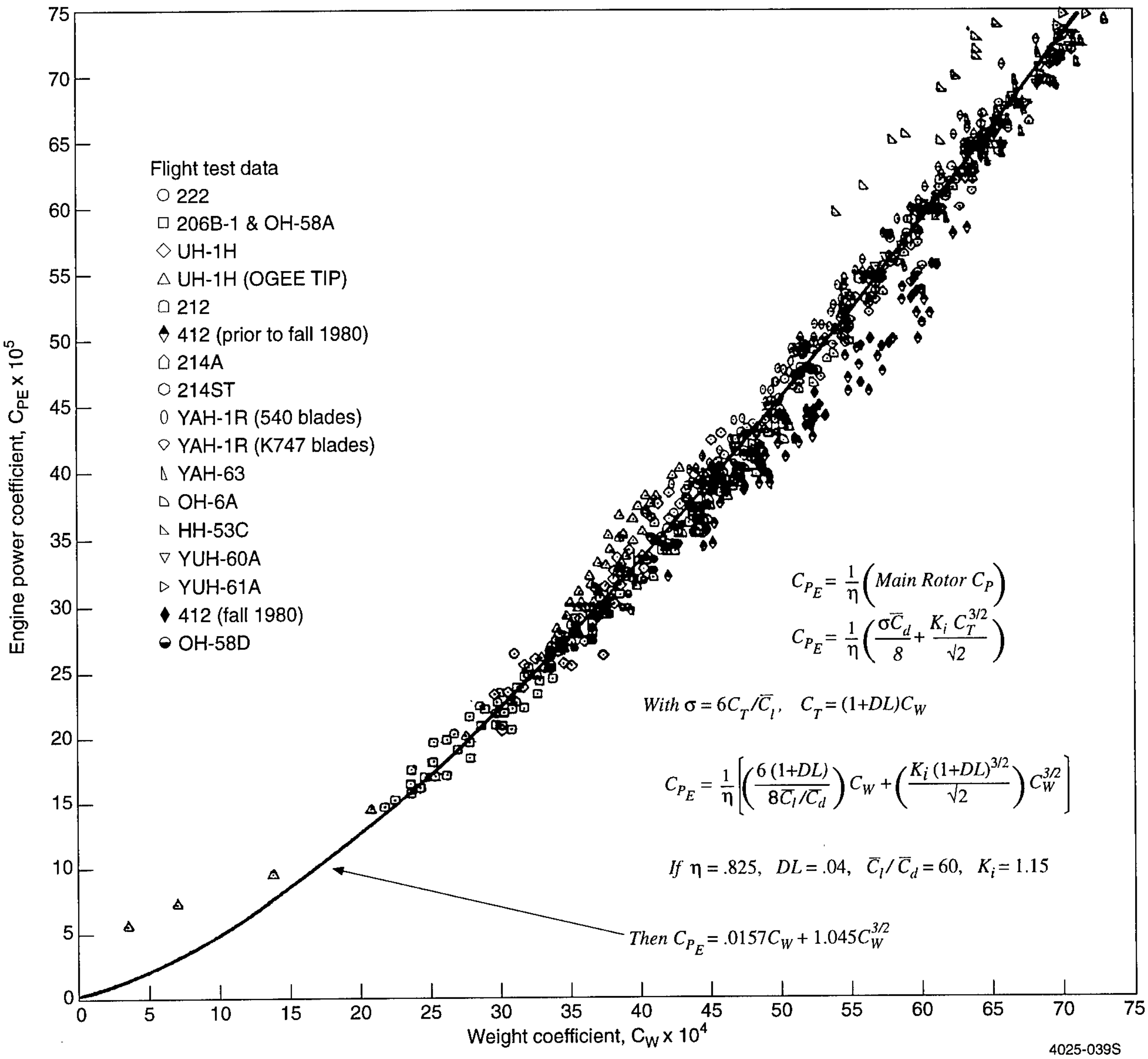

Figure 18. Helicopter $\mu = 0$ Hover Performance Trends As $C_{P_E} = 0.0157\ C_W + 1.045 C_W^{3/2}$

Forward flight performance, however, is influenced by weight and drag. Figure 19 shows how specific range and aircraft speed are influenced by weight changes. Figure 20 shows how specific range and aircraft speed are influenced by aircraft configuration drag changes. The relationships are very different. An increase of a square foot of drag reduces range by 1.5% at best range speed, while an increase of 100 lb of gross weight reduces the aircraft's range by 0.3%. Analytical or empirical methods such as those found in Fluid Dynamic Drag by Hoerner, reference 13, can be used to determine the drag of an aircraft or augment wind tunnel test results. Assessments of the AH-1, Apache, MH-60K, and other armed helicopters put their total drag around 3.27 square meters (40 square ft). External stores such as 16 HELLFIRE missiles, four stations, or 230 gallon fuel tanks on each station contributes approximately 1.0 square meter (10.7 square feet) of parasite drag. The stores support wings contribute approximately .23 square meters (2.5 square feet) of drag. External stores, therefore, reduce the range of helicopters by 25%. The external support system or wing also weigh between 135 kg (300 lb) and 180 kg (400 lb) which also reduces the aircraft's range by 1.5%.

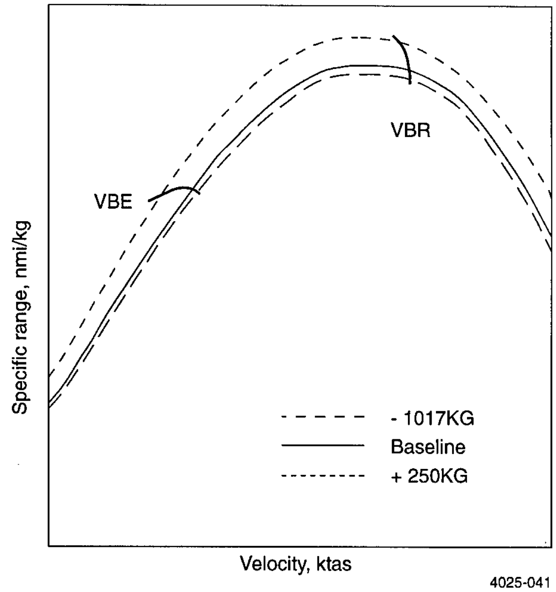

Figure 19. Level-Flight Performance, Specific Range Versus Speed

5.0 DRAG REDUCTION OPTIONS

Location of the weapons has a major influence on the drag associated with a stores arrangement. MIL-STD-1289 states that the clearance for missiles and rockets shall be determined by use of a 5° half-angle cone, evaluated from the outer surfaces of the ordnance to the worst case rotor plane, and to any fixed and moveable portions of the aircraft which may be adjacent to ordnance trajectories. For weapons launch, the origin of the 5° half cone is established as the station location at which the weapon is free of the launch rail or tube. This is consistent with the guidance used to locate stores on the UH-60 and MH-60K and most U.S. armed helicopters. The 5° half-angle clearance cone, including the offset dimension for weapon extremity, is referred to as the "clearance envelope."

Four cases involving worst-case HELLFIRE flyout trajectories were modeled using laser designated weapon system simulation (LDWSS) to confirm that launches stay within the clearance envelope. LDWSS was also used to assess if the clearance envelope criteria was too stringent. LDWSS considers launch platform prelaunch conditions such as pitch rate, roll rate, yaw rate, velocity, and acceleration to generate sets of curves for missile pitch, roll, yaw, cross-range position, and altitude, each plotted against missile CG positions downrange from the launcher. Stores supporting structural deflection were calculated using NASTRAN to establish rail position during missile launch.

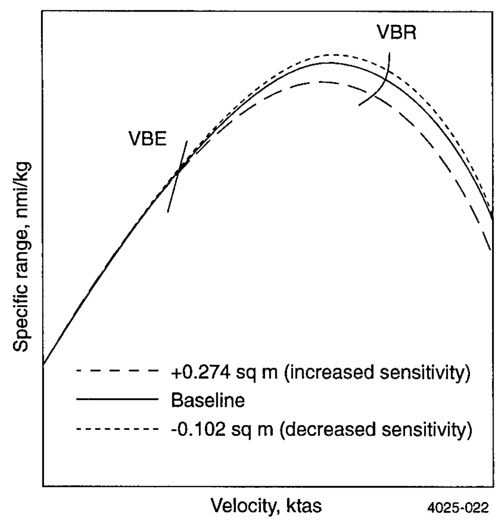

Figure 20. Level-Flight Performance, Specific Range Versus Speed

To derive the trajectory for the single worst case, worst case missile position data was selected from each plot and combined in a three-dimensional CATIA layout. For example, the worst missile yaw outboard from one case is combined with worst missile cross-range path, inboard, from another case. Such combinations would represent extremes of position and attitude which tend to bring the missile close to the aircraft. In spite of this conservative approach, missile extremities remained within the 5° half-angle clearance envelope, Figure 21.

The clearance envelope therefore does establish the waterline and buttline locations for the missile (or rocket) closest to the aircraft structure. Another requirement such as jettison clearance (a 10° fall-away zone) should be checked to ensure that the clearanceenvelope criteria also satisfies the jettison criteria. Placing the next missile to minimize drag impact requires a minimum of diameter separation as defined by Hoerner, Figure 22. This produces an AH-1, Apache, or MH-60K stores support type system Figure 23. This arrangement does reduce the stores, stores support drag impact to around 0.5 square meter (5.0 square feet), and permits the aircraft to carry the standard HELLFIRE launcher with four missiles on each side, which is the fielded configuration on the aircraft above. The estimate for the drag of that arrangement is 0.65 square meters (7.0 square feet).

Figure 23 does reduce the range impact to 10%. To improve on this configuration, fairings could be constructed (similar to the individual launch containers) to surround each missile (Figure 24), or a single conformal fairing that uses integral fuselage mounted fittings to attach the structure. The conformal fairing (Figure 25) also offers the option of reducing the missile separation. A conservative design practice would need to take into account worst case missile fin deflection, missile rocking, rail mounting tolerance, rail-to-rail structural stiffness, and the stiffness of the mounting structure. The result is a package approximately 71.0 cm (28.0 inches)

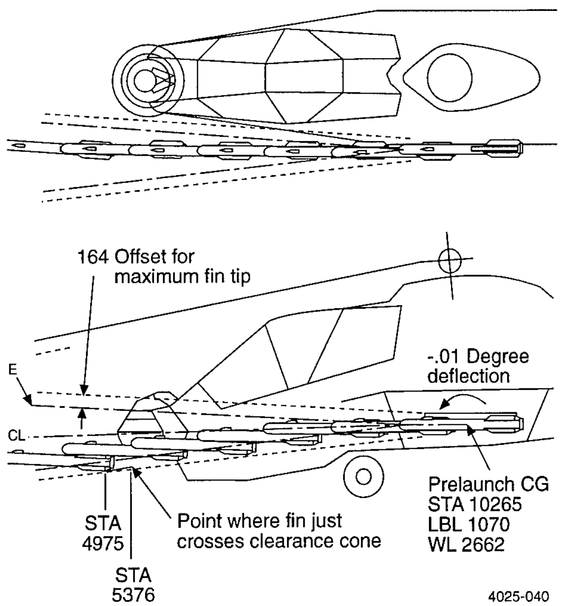

Figure 21. Missile Fly-Out Analysis

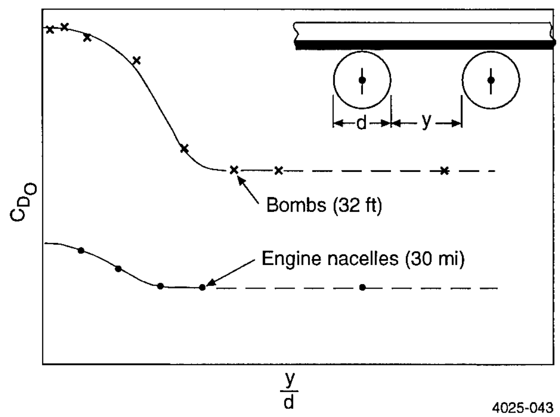

Figure 22. Drag Coefficients of Pairs of Bombs and Tanks (or Nacelles), Respectively As a Function of Their Lateral Distance

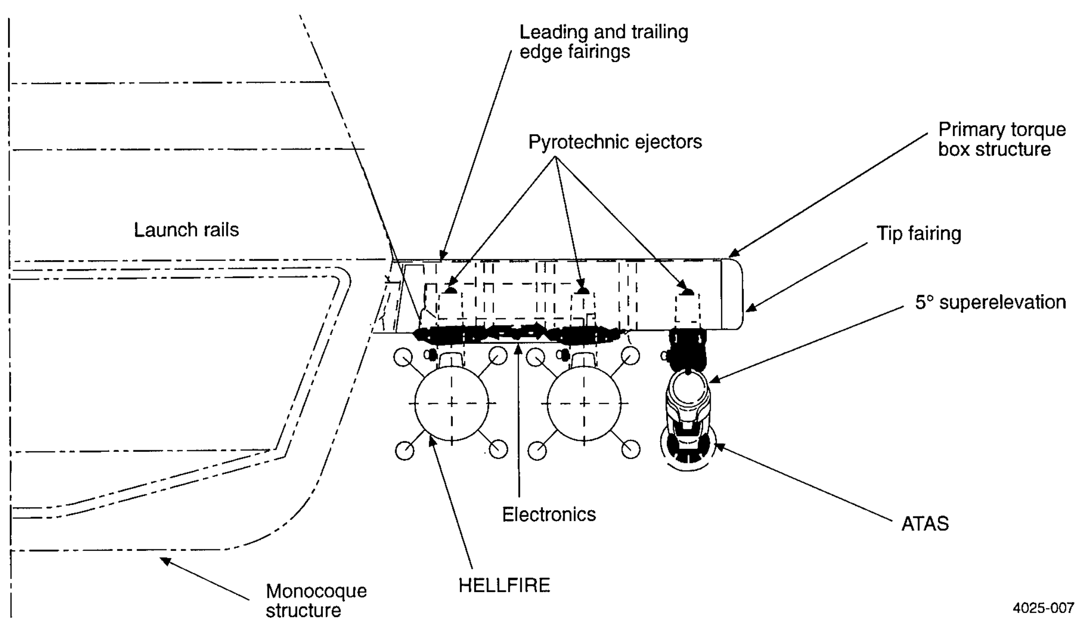

Figure 23. Fixed Wing

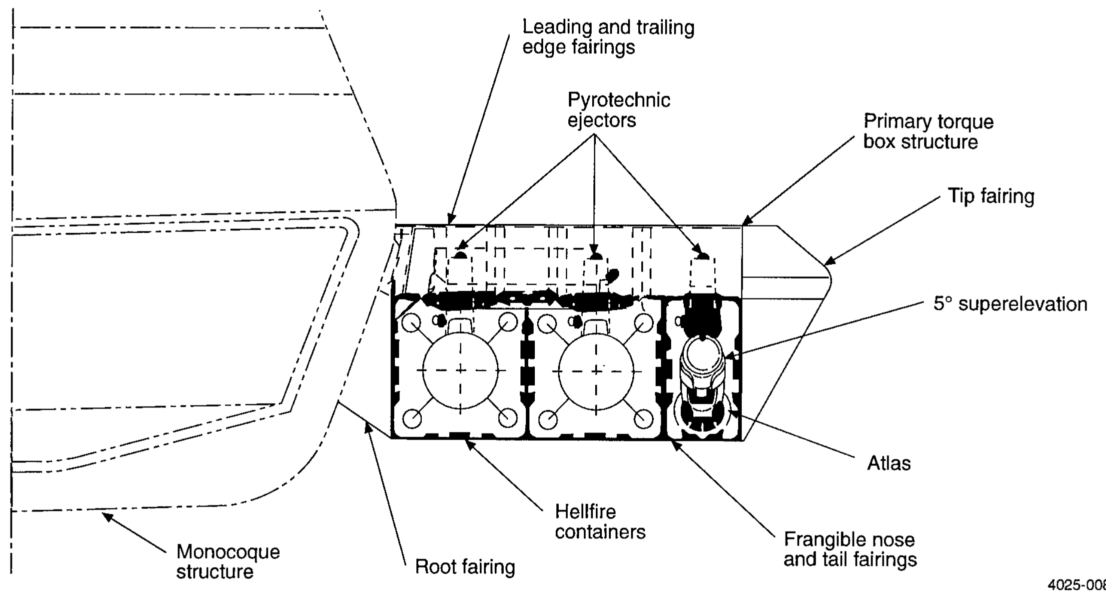

Figure 24. Faired Wing

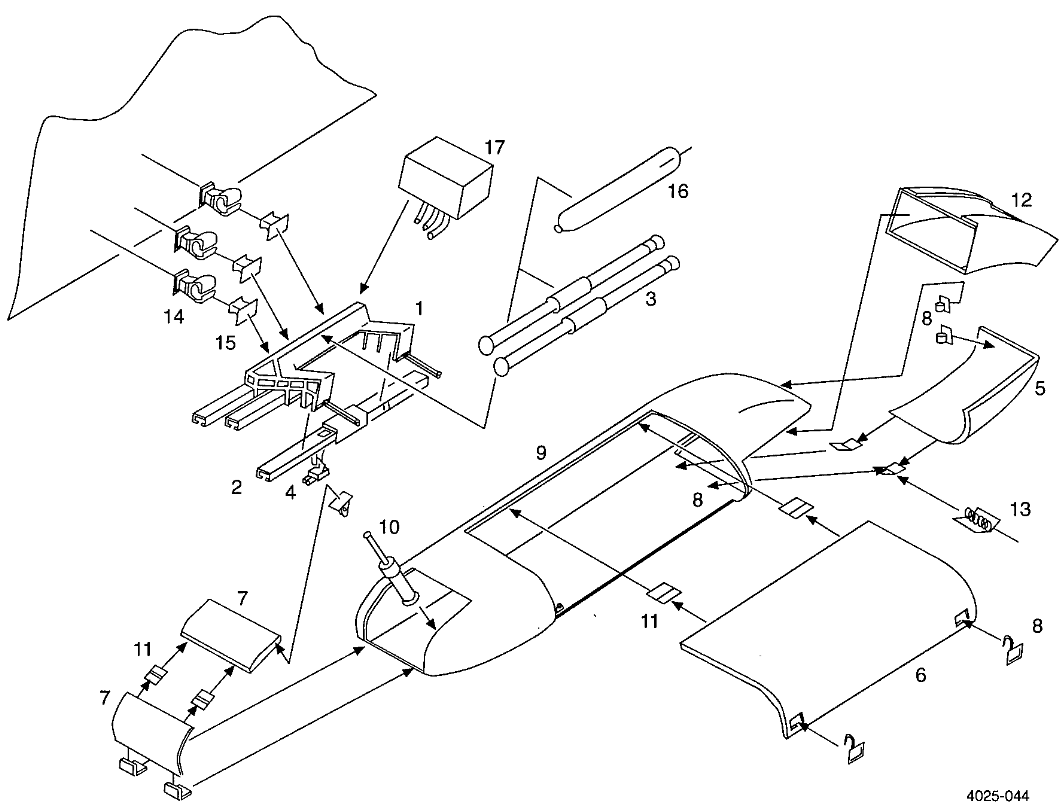

Figure 25. Conformal Weapons Systems

in width, Figure 26. The drag associated in this weapons arrangement (in a pod) is 0.37 square meters (4.0 square feet). The pod requires the incorporation of heat-resistant aft skitts to accommodate missile exhaust. The lower surface must open for jettison of the stores. The complexity of the doors makes this a heavy option (including actuators, hinges, linkages, and seals). Even the surround missile configuration would require a nose and tail fairing to realize the drag benefits.

To reduce the conformal fairing drag further a more aerodynamic shape is required. Figure 27 illustrates what would be required to improve the conformal pod or faired wing aerodynamics. The fairing and the doors are very large and complicated. Another alternative is to internally retract the weapons into the airframe structure, Figure 28.

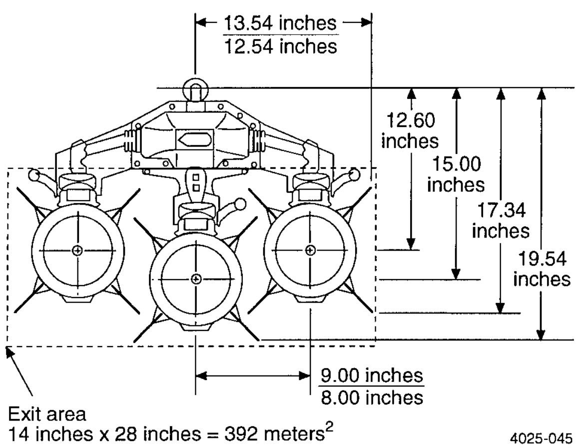

Figure 26. Conservative Design Practice

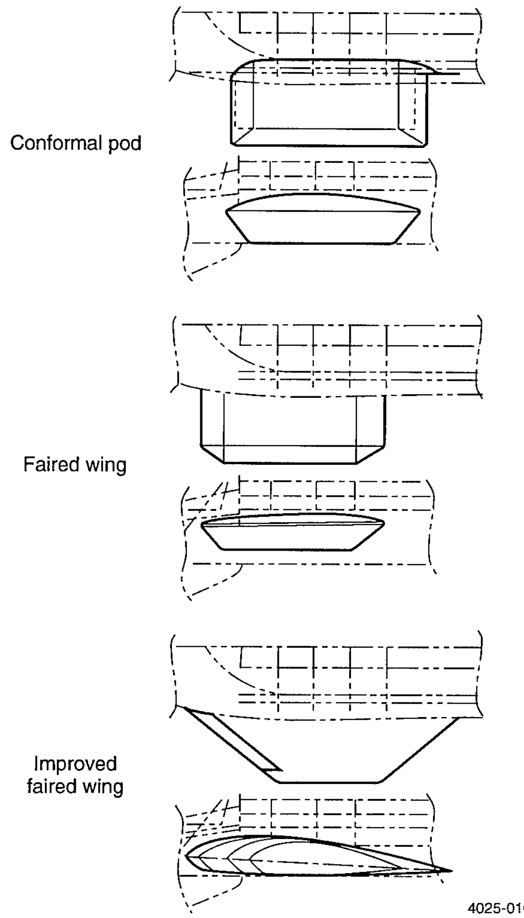

Figure 27. External Installations

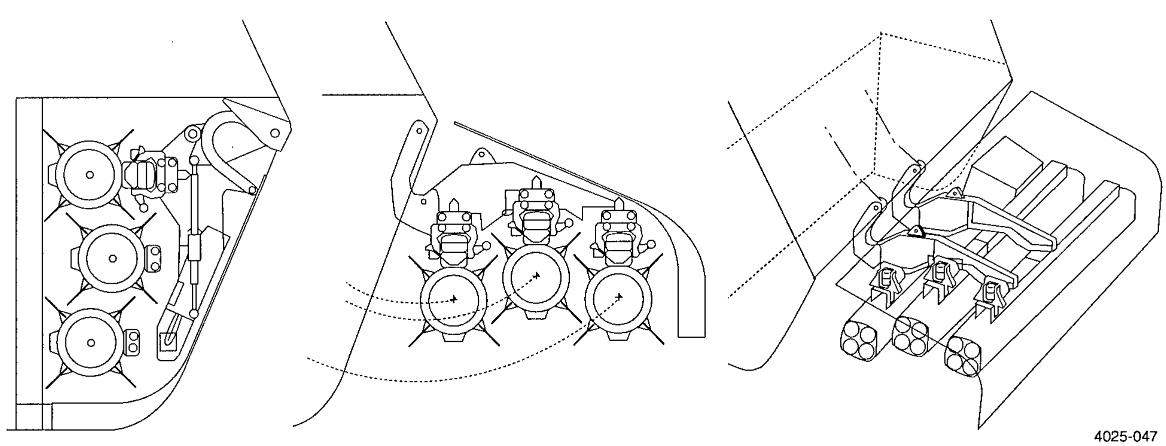

Figure 28. Internal Weapons

Internal weapons produce the best drag solution, but have a major influence on the basic airframe design. External weapons arrangements are compatible with conventional Semimonocoque airframe structure. Internal weapons require a more conventional fixed wing airframe structure. The internal weapons favor a primary structure backbone or central box beam arrangement with lightly loaded exterior panels attached to it. There are a number of advantages to this type of structure including:

- Large number of door and access panels to access equipment.
- Good torsional rigidity.
- Antiplowing box beam for improved crashworthiness.

6.0 CONCLUSION

Rotor, engine, and light-weight structure technologies continue to advance, providing options that would improve the drag characteristics of armed helicopters, Figure 29. Existing aircraft in some cases will be constrained to fairings or simple repackaging approaches. New designs can explore the fixed wing internal weapons approach. The bottom line is fuel savings and the associated cost.

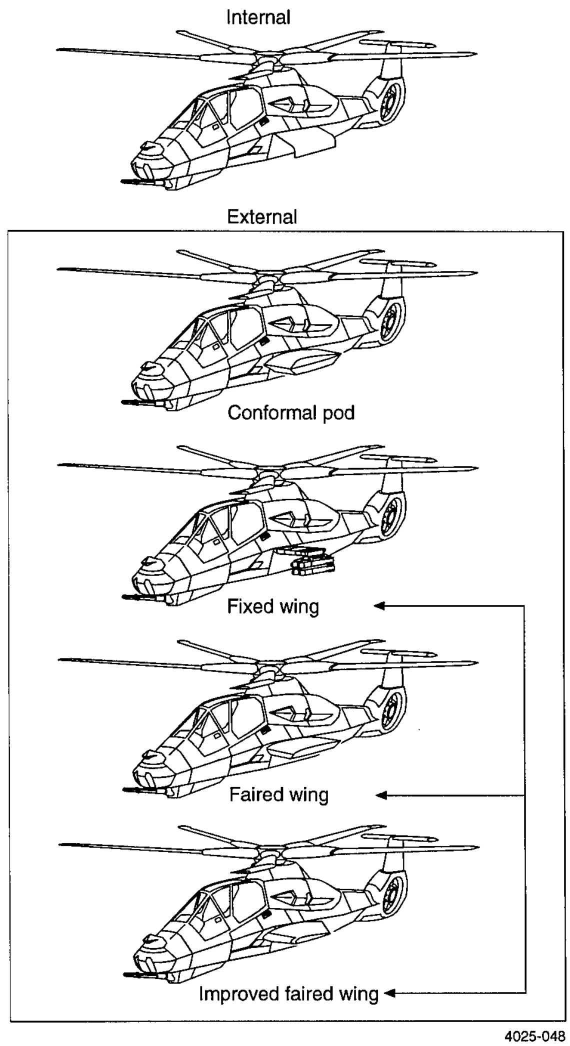

Figure 29. Weapons Installation

LIST OF REFERENCES

1. Garbo, S.P., and Rosen, K.M., "Composites Usage on RAH-66," *Vertiflite*, March/April 1992.

2. Shanley, J.P., Moffitt, R.C., and Davis, S.J., "Systematic Correlation and Evaluation of the EHPIC Hover Analysis," presented at the *46th Annual Forum of the American Helicopter Society*, May 1990.

3. Bliss, D.B., Teske, M.E., and Quackenbush, T.R., "A New Methodology for Free Wake Analysis Using Curved Vortex Element," *NASA CR 3958*, 1987.

4. Quackenbush, T.R., Bliss, D.B., Wachspress, D.A., and Ong, C.C., "Free Wake Analysis of Hover Performance Using a New Influence Coefficient Method," *NASA CR 4150*, 1988.

5. Flemming, R.J., and Erickson, R.E., "An Evaluation of Vertical Drag and Ground Effects Using the RSRA Rotor Balance System," presented at the *38th Annual Forum of the American Helicopter Society*, May 1982.

6. Shanley, J.P., "Forward Flight Data Bank (FFDB) Computer Code," *SER-50352*, 20 July 1990.

7. Keys, C.N., McVeigh, M.A., Dadone, L., and McHugh, F.J., "Considerations in the Estimation of Full-Scale Rotor Performance from Model Rotor Test Data," *39th Annual Forum of the American Helicopter Society*, St. Louis, MO, May 1983.

8. Tarulli, F., "Revisions to the 1985 version of the Generalized Rotor Performance Program (GRP)," *Sikorsky Aircraft SER-510216*, October 1988.

9. Landgrebe, A.J., Moffitt, R.C., and Clark, D.R., "Aerodynamic Technology for Advanced Rotorcraft," *Journal of American Helicopter Society*, Part I - Volume 22, No. 2, April 1997; Part II - Volume 22 No. 3, July 1977.

10. Landgrebe, A.J., and Bennett, Jr., J.C., "Investigation of the Airflow of a Hovering Model Helicopter at Rocket Trajectory and Wind Sensor Locations," *United Technology Research Center Report R77-912573-15*, July 1977.

11. Gressow, Alfred and Myers, Garry C. Jr., *Aerodynamics of the Helicopter*, College Park Press, 1985.

12. Harris, F.D., "Rotary Wing Aerodynamics--Historical Perspective and Important Issues," presented at the *AHS National Specialists Meeting on Aerodynamics and Aeroacoustics*, February 1987.

13. Hoerner, S.F., *Fluid-Dynamic Drag*, published by Sighard F. Hoerner, 1965.

HANDLING QUALITIES

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SUMMARY

The mission performance of an armed helicopter does not only depend on its weapon system's efficiency. Other factors like the helicopter performance and in particular the handling qualities of the overall helicopter/weapon system may significantly affect mission performance. Since handling qualities cover a wide range of aspects which sometimes are difficult to quantify, it is useful to refer to existing standards when defining armed helicopters specifications.

For analytical predictions of handling qualities nonlinear flightmechanical mathematical models are used, and described in this lecture, representing the different components of a helicopter, like the main rotor, the fuselage, powerplant etc. and the interactions between these. For armed helicopters the weapon systems have to be considered in addition by modelling their dynamic and aerodynamic characteristics and the effects on the helicopter behavior during the weapon delivery.

Before using the analytical models for simulating the helicopter responses these models have to be validated. For this purpose dedicated and reliable data bases have to be generated by wind tunnel and flight testing, applying advanced test and data analysis tools.

For evaluation of the overall pilot/helicopter/weapon system modern handling qualities specifications (ADS-33) are outlined which use two different approaches: Following the definition of the operational missions and the environment by the helicopter user (1) the comparison of the rotorcraft characteristics with the quantitative requirements provides an analytical assessment of the level of handling qualities, and (2) the ultimate assessment of the fully equipped vehicle is obtained by flight evaluation performing specific mission related tasks.

Both approaches are discussed in view of the consideration of the effects of the installation of external weapon systems on the handling qualities of the helicopter system.

1. INTRODUCTION

For modern helicopters very high standards are required in regard to mission performance and system qualities. This is valid for both, civil and military aircraft. While for civil applications flight safety and profitability are the prime factors, the military users are asking in addition for adequate combat effectiveness.

The helicopter is required to perform as a dynamic system within the user-defined operational flight envelope (OFE), or that combination of airspeed, altitude, rate of climb/descent, sideslip, turn rate, load factor, and other parameters that limit the vehicle dynamics, required to fulfil the user's mission (Fig. 1). Beyond the OFE lies the manufacturer-defined service flight envelope (SFE), that is derived from aircraft limits as distinguished from mission requirements. This envelope shall be expressed in terms of the parameters used to define the OFE, plus any additional parameters deemed necessary to define the appropriate limits. The inner boundaries of the SFE are defined as coincident with the outer boundaries of the OFE. The outer boundaries of the SFE are defined by one or more of the following: uncommanded aircraft motions, or structural, engine/power-train, or rotor system limits [Ref. 1]. Within the OFE the flight mechanics of a helicopter can be discussed in terms of three characteristics: trim, stability and response.

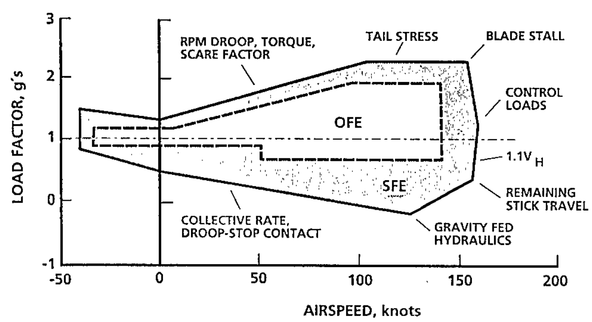


Figure 1: Operational and service flight envelopes [Ref. 1]

Trim is concerned with the ability to maintain flight equilibrium with the controls fixed. Trim conditions include hover, cruise, autorotation, sustained turns but also in general descending or climbing (with air density and temperature assumed to be constant), and sideslipping at constant speed. Stability is concerned with the behavior or tendency of the helicopter when disturbed from its trim condition. The initial tendency is called static stability, the longer term characteristics the dynamic stability. The response of the helicopter stands for its behavior to pilot controls and external disturbances. Typically, a helicopter responds to a single-axis control input with multi-axis behavior, the so-called on-axis and off-axis responses. Cross-coupling is almost synonymous with helicopters.

Trim, stability and control, these fundamentals of flight dynamics, are illustrated in Fig. 2 in the natural modelling dimensions of frequency and amplitude, with the OFE boundary. Vibration, structural loads and steady state performance define the edges of the OFE in this presentation [Ref. 2]. Adequate handling qualities then ensure that the OFE can be used safely, in particular that there will always be sufficient control margin to enable recovery in emergency situations. In a dynamic context, this includes concepts like aircraft-pilot-couplings and agility. Therefore, the dynamic OFE can be defined by the handling qualities of the rotorcraft.

Paper presented at the AGARD FVP Lecture Series on "Helicopter/Weapon System Integration", held in Winchester, UK, 19-20 May 1997; Athens, Greece, 22-23 May 1997, and published in LS-209.

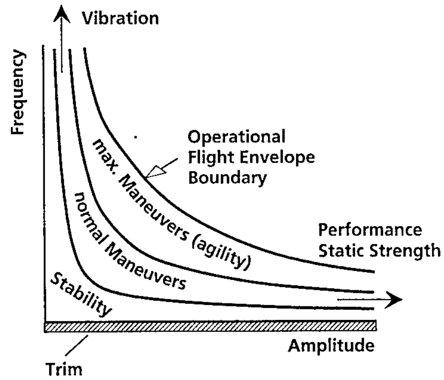


Figure 2 Helicopter flight dynamcis on the frequency-amplitude plane [Ref. 2]

In this understanding the handling qualities of a helicopter fitted with its weapon system amongst them, may significantly affect mission performance, independent from the weapon system's efficiency. A helicopter with good handling qualities offers the following advantages:

- Pilot workload reduction and, consequently, increased crew availability for target detection or other tasks,
- Accurate flight path control during weapon system operations,
- Improved ability to perform evasive maneuvers upon detection by the enemy.

Since handling qualities cover a wide range of aspects which sometimes are difficult to quantify, it is useful to refer to existing standards when defining armed helicopters specifications.

The most comprehensive set of requirements in existence is provided by the US Army's Aeronautical Design Standard 'Handling Qualities Requirements for Military Rotorcraft' (ADS-33), which will be referred to in this lecture [Ref. 3].

Compliance with the criteria of a standard does not necessarily prove that the helicopter characteristics have been optimized as regards to mission effectiveness, but it guarantees that the vehicle will not present objectionable handling qualities deficiencies within the operational flight envelope. Demonstration of compliance with handling qualities standards is therefore one of the main tasks of helicopter manufacturers involved in weapon systems installation. This comparison of the rotorcraft characteristics with the requirements provides an analytical assessment of the level of handling qualities. This is why it is important to perform specific handling qualities' studies when installing external stores on helicopters [Ref. 4].

While these objective assessments are necessary for demonstrating compliance with accepted quality standards, they are still not sufficient to ensure that the helicopter with the weapon system installed will achieve its operational goals. Gaps in the criteria due to limited test data, among other factors, continue to make it vital that additional piloted tests, with a subjective assessment, are conducted prior to acceptance and certification. A helicopter needs to be flight tested to assess its handling qualities in a range of mission task elements (MTE), throughout its intended OFE, including operations at the performance limits to expose any potential handling qualities problem.

2. MATHEMATICAL MODELS OF HELICOPTER FLIGHT DYNAMICS

2.1 Nonlinear Analytical Models

The mathematical description of the helicopter's flight dynamics needs to include the essential aerodynamic, external and internal dynamic, and structural effects that combine to influence the response of the helicopter to pilot's control and external disturbances. The problem is highly complex for unarmed vehicles and becomes even more complex for helicopters carrying weapons and deliver them.

The behavior of a helicopter in flight can be modelled as the combination of a large number of interacting sub-systems. Among these are the main rotor, the tail rotor, the fuselage, the engines, the flight control system, and the empennage with all the forces and moments acting on these elements. In Fig. 3 the orthogonal body-fixed axes system is shown, fixed at the center of gravity of the whole helicopter, about which the vehicles dynamics are referred. The equations governing the behavior of these interactions are developed from the application of the basic physical laws, like Newton's law of motion and the conservation laws, to the individual components.

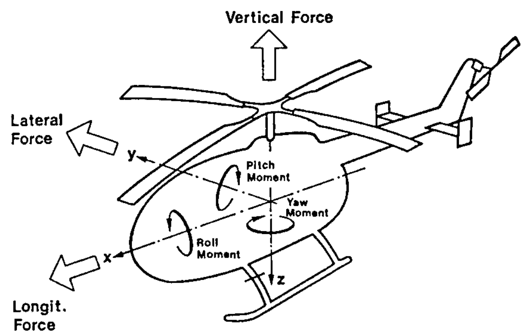


Figure 3: Body-fixed axes system

Unlike the flight dynamics of most fixed wing aircraft, the dynamics of rotary wing aircraft are characteristically those of a high order system. The large number of degrees of freedom associated with the coupled rotor-body dynamics leads to a large number of unknown parameters that have to be estimated. A twelve degree of freedom simulation model structure, as illustrated in Figure 4, is about the minimum required for engineering simulation validation and flight control system design. However, for handling qualities evaluation a six degree of freedom model may be adequate [Ref. 5].

6 DOF Fuselage Dynamics	Rotor/Fuselage Coupling	Inflow/Fuselage Coupling	u w q θ v p ϕ r ψ
Fuselage/Rotor Coupling	3 DOF Rotor Flapping Dynamics	Inflow/Rotor Coupling	β_0 β_{1C} β_{1S}
Fuselage/Inflow Coupling	Rotor/Inflow Coupling	3 DOF Inflow Dynamics	λ_0 λ_{1C} λ_{1S}

Figure 4: Helicopter simulation model structure [Ref. 5]

The classic form of the resulting equations of motion of an aircraft with six degrees of freedom in body-fixed axes is presented in Figure 5. This formulation in physical dimensions includes the inertial translational and rotational velocities in the moving axes system, the Euler angles defining the orientation of the fuselage axes with respect to earth, the helicopter mass and the moments of inertia about the reference axes. The external forces and moments are written as the sum of the contributions form the different helicopter components.

$$X_{aero} + X_{inertia} = m(\dot{u} + qw - rv) + mg\sin\vartheta$$
$$Y_{aero} + Y_{inertia} = m(\dot{v} + ru - pw) - mg\cos\vartheta\sin\varphi$$
$$Z_{aero} + Z_{inertia} = m(\dot{w} + pv - qu) - mg\cos\vartheta\cos\varphi$$

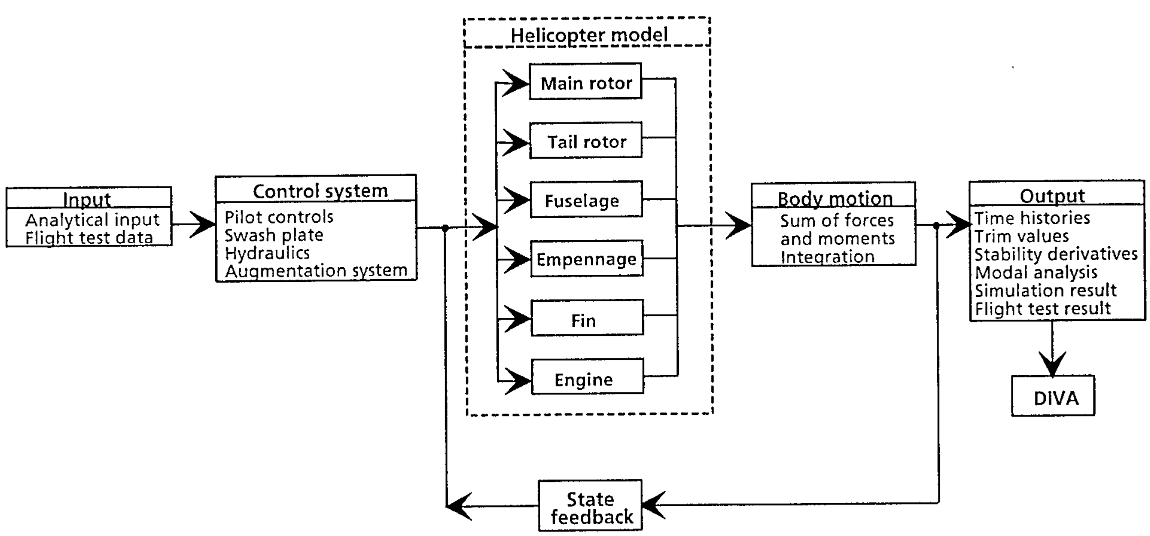
$$L_{aero} + L_{inertia} = I_{xx}\dot{p} - I_{xz}\dot{r} + qr(I_{zz} - I_{yy}) - I_{xz}pq$$
$$M_{aero} + M_{inertia} = I_{yy}\dot{q} + pr(I_{xx} - I_{zz}) + I_{xz}(p^2 - r^2)$$
$$N_{aero} + N_{inertia} = I_{zz}\dot{r} - I_{xz}\dot{p} + pq(I_{yy} - I_{xx}) + I_{xz}qr$$

- all terms formulated in physical dimensions
- left hand side include rotor inertia forces
- these inertia forces are essential for rotational motion

Figure 5: Equations of body motion

In Figure 6 the blockdiagram of a typical mathematical model of helicopter flight dynamics in outlined. In general, it includes the elements input, control system, helicopter model, body motion, output, and feedback control system. Depending on the application area, the specific models of the individual elements may be very simple or highly sophisticated. The models should be as simple as possible but, on the other side, for flight dynamics, the modelled frequency range in terms of forces and moments needs to cover two or three times the range at which normal pilot and control system activity occurs. Therefore, for manual pilot control inputs the model validity up to about 10 rad/s is probably good enough, for high gain feedback control systems modelling up to 25 - 30 rad/s may be required. If the model will be used to drive a helicopter flight simulator severe computing time constraints may limit the details in the representation of this real-time simulation model.

The modelling challenge is dominated by the main rotor and its induced flow field. Concerning rotor dynamics, a correct representation is necessary for at least the first mode of blade bending in flapwise direction. For flightmechanical purposes a hingeless rotor can be simulated by an articulated rotor with an equivalent hinge-offset that provides the same first bending mode frequency under rotation. An improvement can be obtained when blade lead-lag and torsion are also taken into account. The induced flow field has to be modelled for low speed flight as well as for the higher speed regime. Often constant or trapezoidal downwash distributions are used, and other distributions representing the nonlinear variation along the blade span and around the azimuth are available, just as specific formulations for the dynamic inflow [Ref. 6]. For specific applications, like vibration analysis or rotor design, very detailed rotor models are used,



Helicopter model

Input: Control variables and state variables (feedback)
Output: Forces and moments

Body motion

Input: Sum of forces and moments of all modelled components
Output: Integration of state variables of CG motion (6DOF)

Figure 6: Blockdiagram of helicopter simulation program

including freewake or prescribed wake analysis and detailed structural representation of the rotor e.g. finite elements analysis. In general, these detailed models don't meet the requirements of a flight dynamics model, on the one side the required computer power is much to high, on the other side most of these models are not formulated up to now for maneuvering helicopters.

The aerodynamic characteristics of the fuselage including the weapon installation are normally given as input data for the computer code, such as lift, drag, and the pitch, roll, and yaw moment coefficients about the center of gravity for different flight conditions. These have to be determined in advance e.g. by wind tunnel tests with a similar model fuselage. The horizontal and vertical tailplane aerodynamic characteristics are given as separate input data in order to account for the influence of the main rotor wake and the wake generated by the fuselage.

The Figures 7 to 10 present some basic assumptions for the modelization of the helicopter components in a typical flight dynamics model. In Figure 11 an example for the discretisation of the model for the BO 105 helicopter is given, with the objective to run this model in real-time on a state-of-the-art computer.

- forces and moments of main rotor acting on cg
- blade element theory
- rigid blades with flapping and lagging DOF, no torsional DOF
- coincident flapping and lagging hinges
- equivalent hinge and damper for modelling hingeless (elastic) blades
- nonlinear aerodynamics, quasi stationary
- table look up for aerodynamic coefficients, dependent on local inflow and Mach number
- trapezoidal downwash, dynamic inflow like Pitt & Peters
- dynamic inflow extension to "virtual inertia"
- tip loss factor
- switch variable for sense of rotation (counterclockwise USA GERMANY UK) (clockwise FRANCE RUSSIA)

Figure 7: Basic assumptions for main rotor model

- forces and moments of tail rotor acting on cg
- local aerodynamic state variables
- tip path plane model
- only primary design parameters included in rotor description
- linear aerodynamics (small angle assumption)
- no tip path plane dynamics (algebraic formulation)
- no cyclic pitch

Figure 8: Basic assumptions for tail rotor model

- aerodynamic forces and moments of fuselage acting on cg
- table look up for local angle of attack α and local angle of sideslip β
- coefficients from model wind tunnel measurement
- drag of rotating rotor hub normally included in tables
- downwash interference

- aerodynamic forces and moments of horstab and fin acting on cg
- table look up for local angle of attack α and local angle of sideslip β
- coefficients from model wind tunnel measurement
- downwash interference

Figure 9: Basic assumptions for fuselage, horizontal stabilizer, and fin models

- engine torque due to fuel flow ~ first order system
- rpm variations due to torque variation ~ first order system
- Governor ~ PID controller
- collective lead-lag motion implemented

- modelled by transfer function

$$f(s) = \frac{Ke^{-\tau s}}{s^2 + T_1 s + T_2}$$

- parameters identified from frequency sweep

Figure 10: Engine and rpm governor, actuator dynamics

- sample rate ~ 5 msecs
- corresponding azimuth step size 12.8 deg
- 4 individual blades
- 10 segments based on equal annulii areas of rotor disk
- flap and lead-lag degree of freedom
- nonlinear aerodynamics, table look up for Mach and α
- integration scheme 4th order Runge-Kutta
- implemented on an ALPHA machine
- running in realtime

- *implemented on the AD 100*
- *needs ~ 2 msecs for one cycle*

Figure 11: Discretisation for BO 105 simulation

With these six degree-of-freedom nonlinear models, the solutions for the three characteristics of helicopter flight mechanics trim, stability and response can be determined. A trimmed flight condition is defined as one in which the rate of change of magnitude of the helicopter's state vector as well as the resultant of the applied forces and moments are zero. The trim solution of the equation of motion is represented by the zero of a nonlinear algebraic function, where the controls required to hold a defined equilibrium state are computed. With respect to handling qualities, trim associated problem areas include the prediction of control margins and performance. Figure 12 presents a typical representation of flight mechanics results for trim conditions. The behavior of the helicopter when disturbed from its trim condition is described by the stability. The solution of the stability problem is found by linearizing the equations of motion about a particular trim condition and computing the eigenvalues of the aircraft system matrix. The stability refers to small motions about the trim condition and describes the helicopter's tendency to return to or to to depart from the trim point, if disturbed. A typical representation of the stability characteristics of a helicopter is given in Figure 13. The response solution of the equations of motion is found from the time integral of the forcing function and allows the evolution of the helicopter states, forces and moments to be computed following disturbed initial conditions, and/or prescribed control inputs and external disburbances. In Figure 14 a typical helicopter time response following a control input is presented.

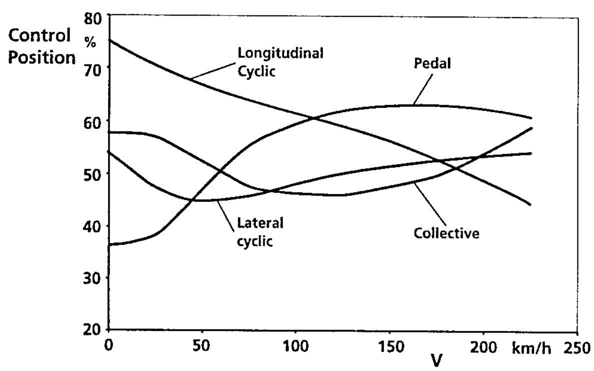


Figure 12: Trim conditions of BO 105 helicopter

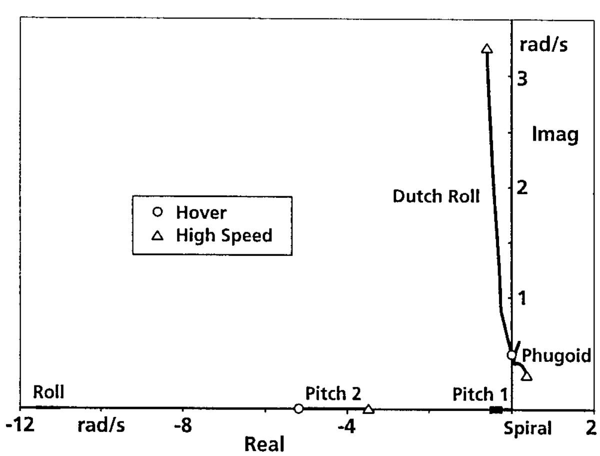


Figure 13: Stability characteristics of BO 105 helicopter

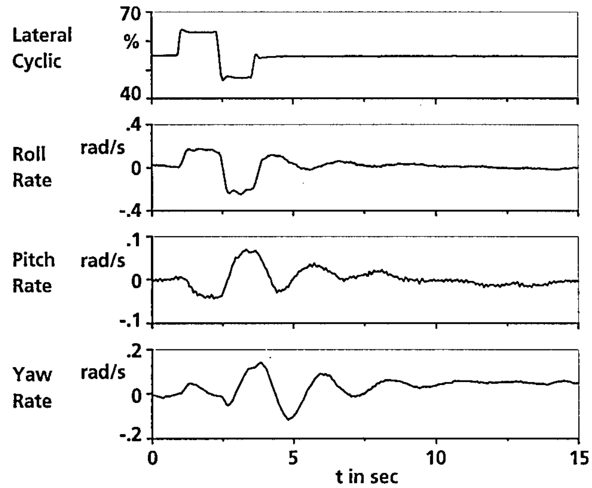


Figure 14: Typical helicopter time response

2.2 Linear Analytical Models

For specific applications in handling qualities analysis and in particular for control system design and optimization linear models of the helicopter are required. These linear models about different operating points or trim conditions can be used in establishing the stability and control characteristics of the vehicle and for a systematic development and design of the vehicle flight control system. In addition, the linear models are easy to comprehend and they usually form the basis for handling qualities evaluations. In general, there are three different methods available for developing the helicopter linear model about a given operating point (Figure 15).

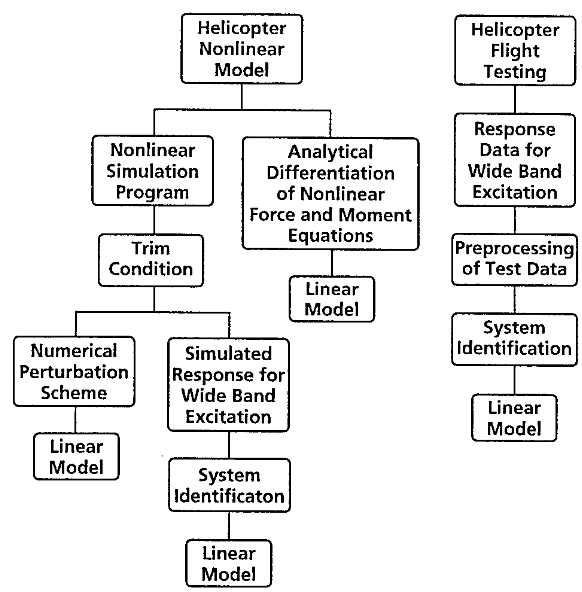


Figure 15: Helicopter linear handling qualities model [Ref. 5]

An often used method is to obtain the linear model from a global nonlinear simulation model through a numerical perturbation scheme. In this method, using a nonlinear flight simulation model, the helicopter is first trimmed at a given flight condition. From their equilibrium values, the states and controls are perturbed one at a time to obtain the changes in body forces and moments. Then the stability and control derivatives are obtained as the ratio of change in corresponding force or moment and the perturbation size of the state or control. Though simple and straightforward, the method can be very sensitive to the perturbation size which itself may be dependent on the flight condition. In order for successful implementation of the numerical perturbation scheme, it is often necessary to establish first the perturbation sizes that will result in appropriate stability and control derivative values at various flight conditions.

The second method is to obtain the stability and control derivatives through analytical differentiation of the force and moment equations. Due to the complexity of the helicopter force and moment equations, analytical differentiation by manual means may become formidable. However, the task involved gets simplified somewhat by the use of symbolic processing programs. The advantage of this method is that once an analytical linear model is obtained, it can be used for parametric studies on a routine basis.

The third method is to obtain the linear model from simulated nonlinear response data through system identification. Using the global nonlinear simulation program, the helicopter is trimmed at a particular flight condition. From this trim condition, the helicopter response data is obtained for wide band excitation in various control channels and measurement noise can be include. From the input-output data, linear models are obtained that best fit the response data. The advantage of this method is that once the methodology is established, the same may be used to obtain linear models from actual flight test data.

2.3 System Identification

All the three methods described above assume that a very good nonlinear model of the helicopter is available for linear model extraction. In the nonlinear model development, often there are many assumptions and approximations made to represent the complicated aerodynamic effects such as rotor-body aerodynamic interference effects, body aerodynamics, etc. Thus it is required to develop a very good nonlinear model before any of the linear model extraction methods can be applied. Hence, the only way of circumventing the problem of the nonavailability of a good nonlinear model for linear model extraction it to obtain the linear models directly from flight test data using system identification. Thus, in principle, this method complements the linear model extraction from simulated response data. The vehicle is flight tested and input-output data is recorded about a trim condition. The type of input selected is such that it has enough frequency content to excite all the dynamic modes and degrees of freedom of interest and the magnitude of the input is limited to keep the magnitude of the vehicle response from trim in the linear range. Using the vehicle input-output data from the trim flight condition, linear models are extracted through system identification [Ref. 7].

Four important aspects of system identification have to be carefully treated (Figure 16):

- Importance of the control input shape in order to excite all modes of the vehicle dynamics motions,
- Type of rotorcraft under investigation in order to define the structure of the mathematical models,
- Selection of instrumentation and filters for high accuracy measurements,
- Quality of data analysis by selecting most suitable time or frequency domain identification methods.

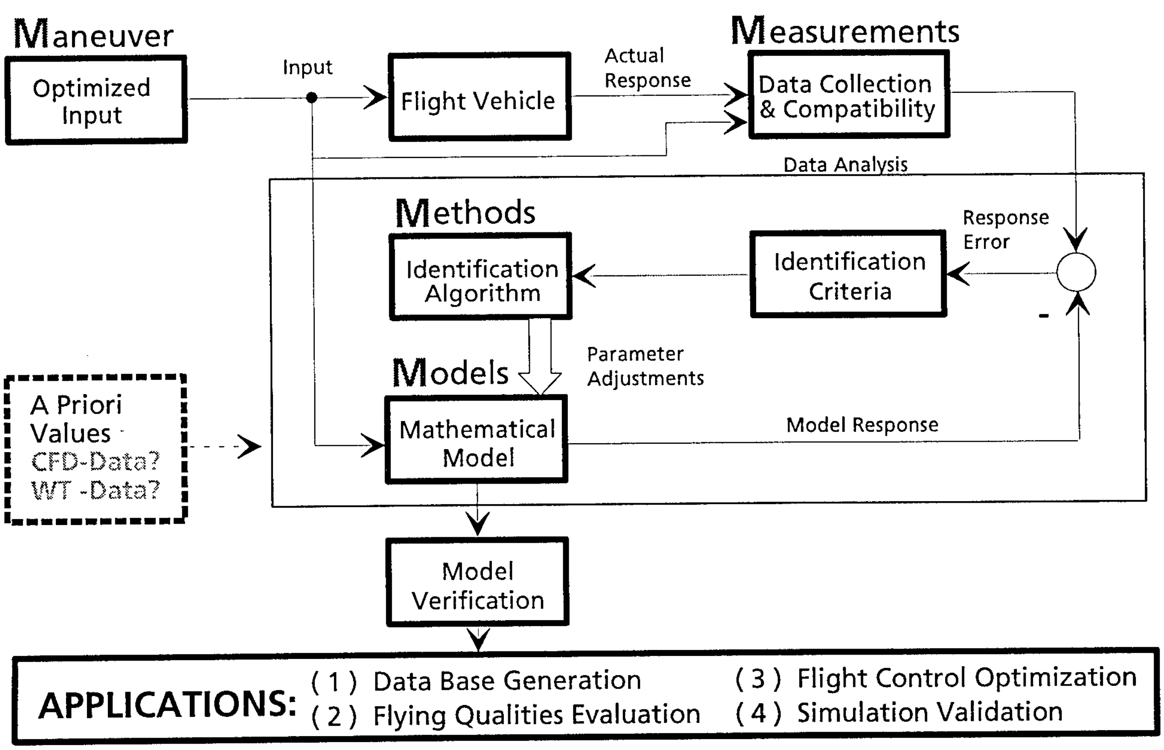


Figure 16: Principle of rotorcraft system identification [Ref. 7]

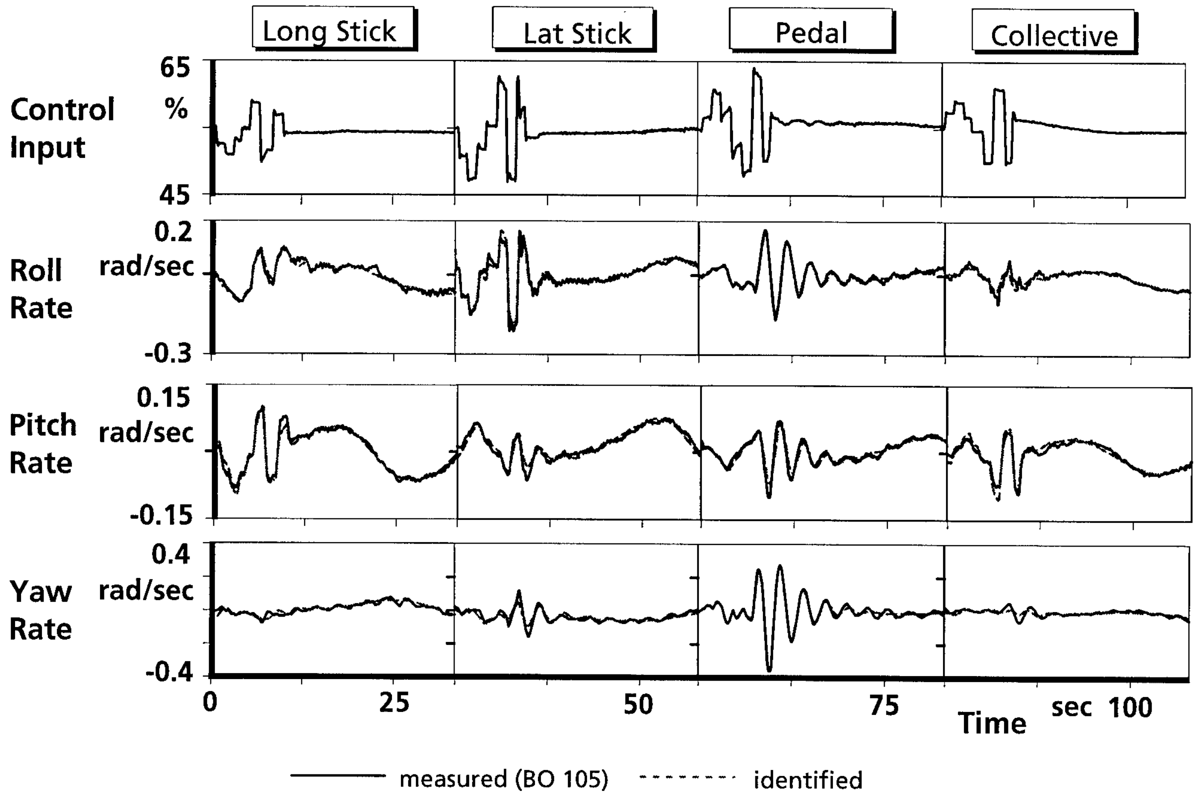


Figure 17: Helicopter system identification results

These requirements must be carefully investigated from a physical standpoint in order to define and execute a successful experiment for system identification. Figure 17 presents typical results obtained by system identification procedures from flight test data [Ref. 8].

For a new vehicle under development, the linear model extraction from flight test data is feasible only after the prototype of the vehicle is available. Thus, considerable insight into the problems associated with the model extraction peculiar to the vehicle under development can be gained by using the simulated response data. Also, experience gained through model extraction from simulated response data may be fruitfully used in the planning and execution of subsequent flight testing and the model extraction from flight test data.

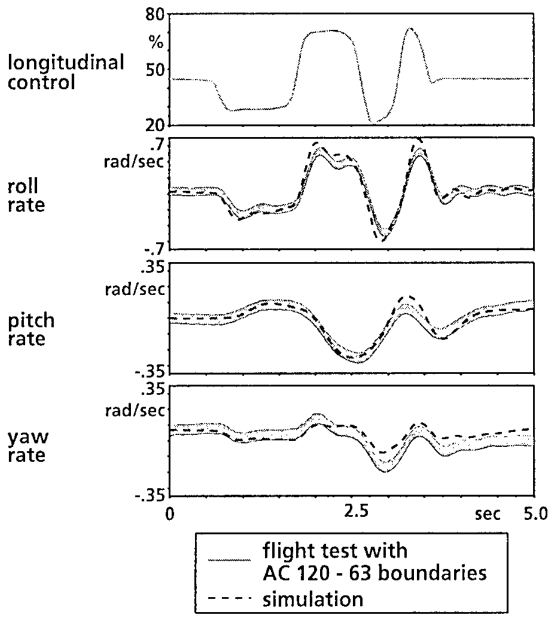
2.4 Effects of External Stores

The installation of external weapon systems effects changes in parameters of the basic aircraft which determine the handling qualities of the helicopter/weapon system. Main influence is on the following parameters:

- Increase of the moment of inertia in pitch, roll and yaw directions. Lateral mounted installations mainly increase roll inertia and somewhat yaw inertia; installations under the nose of the helicopter mainly increase pitch and yaw inertia.
- Shift of the center-of-gravity position. For nose mounted stores the CG is removed to a more forward position. That may result in an unfavourable CG position or range.
- Increase of the mission weight of the aircraft. This will reduce the angle-of-attack stability (the destabilizing effect of the rotor increases with increasing rotor thrust).
- Modification of the aerodynamic characteristics of the aircraft. Of special importance are the aerodynamic fuselage pitch, roll and yaw moment coefficients and the contribution of the tailplanes to these coefficients.

In addition to these influences, as a result of store release and weapon delivery, the helicopter motions, rotor tip path plane excursions and the required pilot control responses may be affected dramatically. These short term aspects have to be investigated using the nonlinear flight dynamic models in piloted ground-based simulations. For this purpose the transient forces which drive the short term maneuvers have to be determined in specific models and integrated in the overall simulation model of the helicopter. Examples for the numerous effects possible due to store release may be the aerodynamic forces generated on the horizontal stabilizer or other parts of the helicopter from the blast of the weapon, and the impulse at a particular point of the vehicle from gun firing.

The benefits of investigating these effects on the helicopter handling qualities prior to the integration of the weapon system hardware is obvious. Advanced mathematical models of the flight dynamics of the helicopter/weapon system are the basis for these studies and for reliable piloted simulation trials.



AC 120-63 Validation Tests		
(3) Control Response	TOLERANCE	FLIGHT CONDITIONS
(a) Longitudinal	Pitch Rate - ± 10% or ± 2°/sec	Hover Augmentation On/Off
(b) Lateral	Roll Rate - ± 10% or ± 3°/sec	
(c) Directional	Yaw Rate - ± 10% or ± 2°/sec	

Figure 18: Requirements and model validation for helicopter simulators

3. DATA BASES FOR VALIDATION

3.1 Validation Process

Analytical models are the primary tool for the first assessment of handling qualities, for the design and integration of subsystems like automatic flight control systems or weapon systems, and for the preparation of piloted simulation tests. These mathematical models, linear or nonlinear, are used throughout the entire design and development process of the helicopter with various levels of fidelity. Fidelity is normally judged by comparison with test data, both model and full scale. In doing so, three aspects need to be addressed in course of this validation process:

- Level of fidelity of the model required for a specific application,
- Data quantity and quality required for the validation,
- Tools available to support the improvement of the fidelity of the model.

These aspects are on the one side not independent form each other, on the other side the appreciation depends to a high degree on the actual application of the model under consideration. As an example, Figure 18 shows requirements for helicopter simulator qualification as established by the FAA [Ref. 9]. The quantity of the required validation flight test depends on the simulator level, the flight conditions and the maximum tolerances between flight test data and simulator model response are determined in detail. In order to ensure compliance with the criteria, the analytical model response in general has to be improved in some respect. This can be achieved by try-and-error methods, considering that the highly coupled, multi-input multi-output response of a helicopter may be difficult to adjust. Two approaches to tackle this problem more systematically may be helpful. One, where the model parameters are physically based and where the modelling element of interest is isolated from the other components through prescribed dynamics, the so-called open-loop method [Ref. 10]. Figure 19 presents the principle of this method using experimental data of subsystems

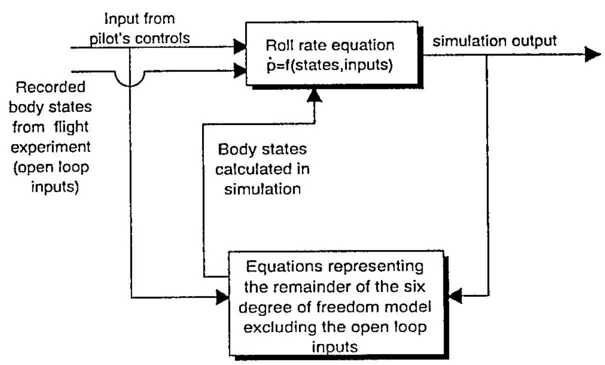
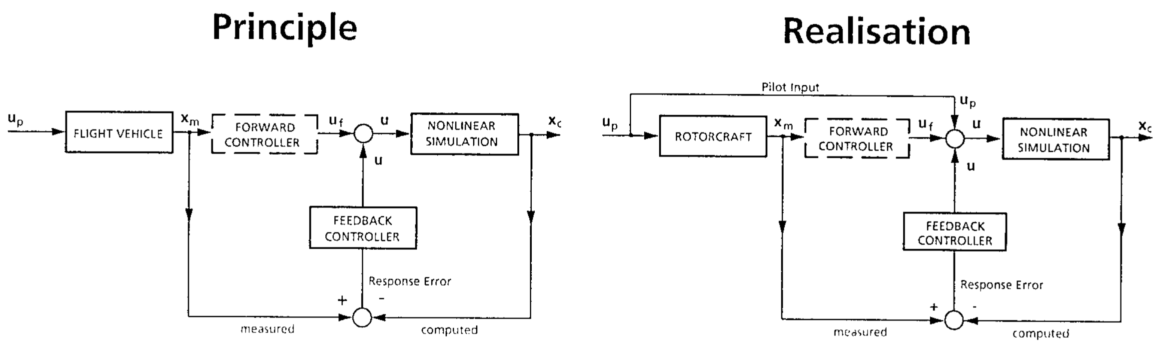


Figure 19: Principle of open loop simulation [Ref. 10]

or recorded states as simulation inputs to reduce model complexity. The other method calculates the degree of distortion of the physical rotorcraft parameters required to match the test data. In Figure 20 the principle of this inverse simulation concept is introduced which allows to determine control perturbations necessary to fit the model output to the flight test data (Figure 21).

3.2 Wind Tunnel Tests

For the validation process of a mathematical model, the data bases available are of high significance. In order to accurately estimate the aerodynamic characteristics of airframes and other bodies of complex shape, wind tunnel tests are still the best method. For handling qualities studies the following types of tests can be envisaged providing the airframe data required:



○ Feedforward represents inverted linear Model of nonlinear Simulation

○ Feedback compensates Errors caused by Nonlinearities of Simulation Program

○ Feedforward replaced by measured Pilot Input
- Matches primarily quick initial on - axes Responses

○ Feedback implements diagonal control scheme with
- P - Controller for pitch and roll attitudes and accelerations
- PI - Controller for angular rates and vertical speed

Figure 20: Principle of inverse simulation [Ref. 10]

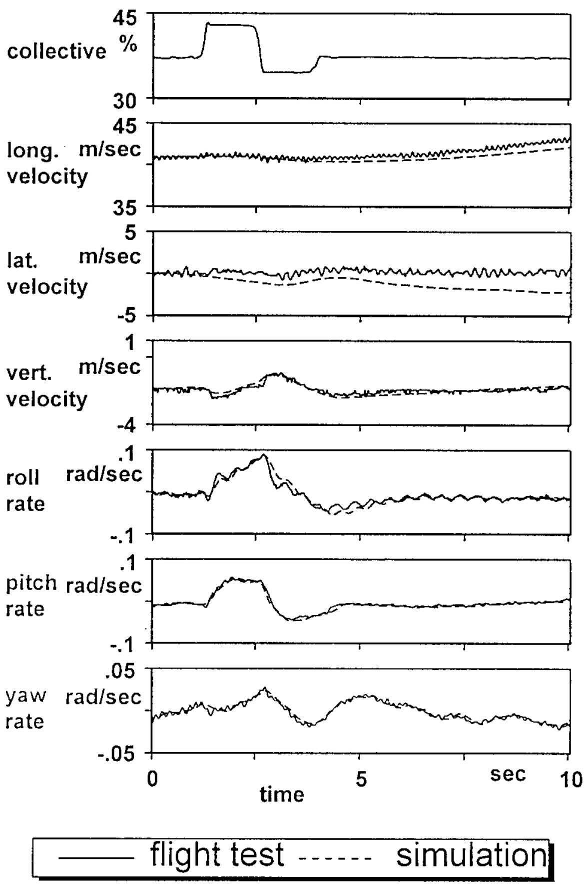


Figure 21a: Inverse simulation results

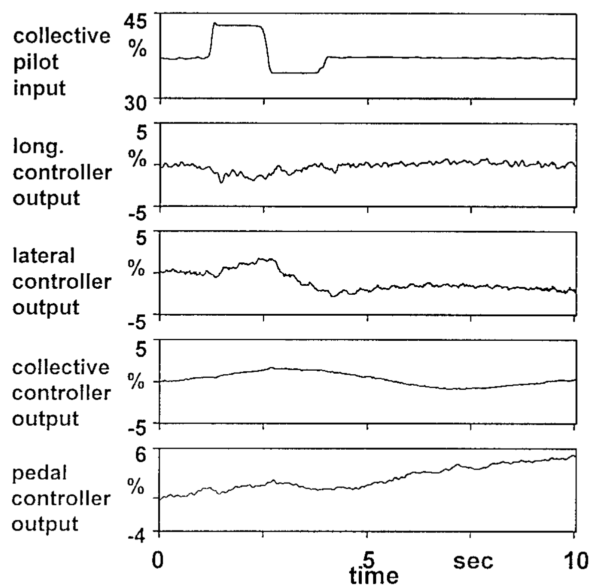


Figure 21b: Inverse simulation controller outputs

- Basic uncoupled tests providing data for trim states and stability studies,
- Tests providing airframe aerodynamic characteristics for simulation programs,
- Powered model tests to study rotor/airframe interaction problems.

The data for trim states and stability studies are usually collected during extensive drag measurement in the wind tunnel, required as a basis for performance calculation. During these tests it is important to check that the aerodynamic characteristics of the fuselage fitted with external stores may not significantly modify longitudinal trim, particularly on small or medium helicopters where the store installation's aerodynamic influence is relatively high compared to that of the basic fuselage. In most cases the stores installation generates a nose-down pitching moment due to the fact that the stores are installed below the helicopter's center of gravity. Other possible causes for a additional pitching moment include the reduction of the stabilizer's download and the wake effects of stubwing mounted stores. Normally a pitch down effect increases hub stresses under load factor during turns and pull-ups, and decreases static longitudinal stability. Possible corrective actions for too high differences between the armed helicopter's and the clean helicopter's pitching moment include:

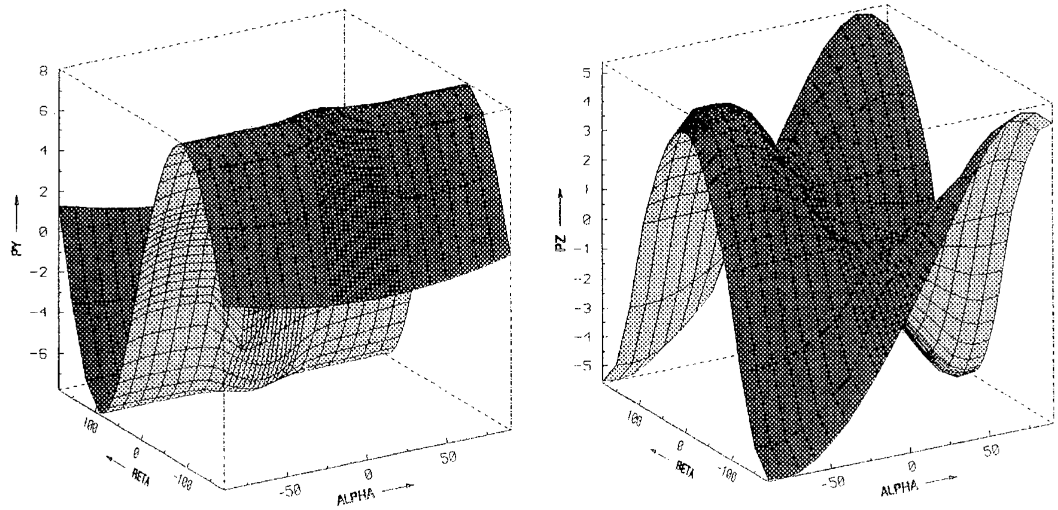


Figure 22: Side force and vertical force coefficients for a typical helicopter fuselage

- Stabilizer setting modification, provided this modification remains limited in view of the unarmed configuration or after store release,
- Modification of shape or position of stores installation.

These modifications usually have a significant influence on the drag of the overall system [Ref. 4].

The knowledge of the helicopter's longitudinal and lateral characteristics is necessary in order to study trim states and handling qualities. Most of the helicopter simulation programs use wind tunnel test data to compute aerodynamic forces and moments acting on the airframe. Pure analytical prediction methods are not accurate enough to establish such a data base, mainly due to the difficulties incurred in the calculation of fuselage characteristics, taking into account boundary layer separation and interference effects. In addition, advanced CFD-codes still need extremely high computer power for calculating these data.

The accuracy required of airframe aerodynamic characteristics depends on the flight conditions to be simulated. For hover and low speed flight, airframe aerodynamic forces are low compared to those of the main and tail rotor. It is therefore not necessary to know the airframe characteristics for every incidence-sideslip combination that could occur in these flight conditions. On the other hand, at cruise speeds airframe aerodynamic forces have high influence on the helicopter's equilibrium and need to be accurately modelized. This leads to the definition of two kinds of wind tunnel runs, depending on the incidence-sideslip range:

- Coupled sweep runs providing aerodynamic characteristics for every incidence-sideslip combination within the (α, β) range for forward flight.
- Large angels un-coupled sweeps: α varying from -90° to +90° for $\beta = 0°$ and β varying from -180° to +180° for $\alpha = 0°$. Interpolation formulas provided are accurate enough to estimate the characteristics for other large incidence-sideslip combinations since this essentially corresponds to hover and low speed flight.

In Figure 22 the yaw moment coefficients for a typical helicopter fuselage are presented for incidence-sideslip sweeps. For the particular armed helicopter configuration, the weapon installation's aerodynamic characteristics need to be measured once it has been fitted on the fuselage to take into account the interference effects. Consequently, two series of runs must be performed: the first with a clean fuselage for clean aircraft data and the second with the weapon installation fitted on the fuselage for armed aircraft data.

As an example for tests providing airframe characteristics Figure 23 shows the clean configuration of the NH90 1:10-scale fuselage model as tested by NLR in the Netherlands. Different configurations with external weapon systems installed have been investigated in order to provide the data base required during the design and development phase of this helicopter project [Ref. 11].

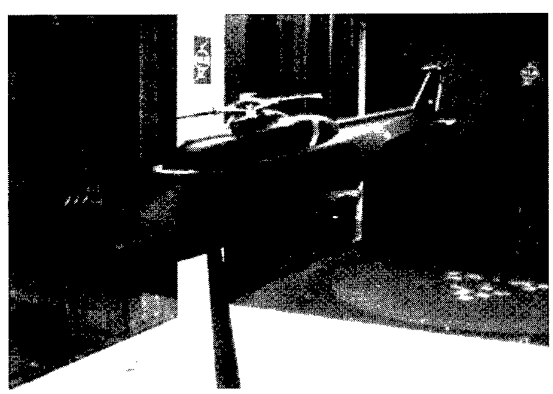


Figure 23: Fuselage model (1/10-scale) of NH90

Powered model tests are required to mainly study rotor wake/airframe and rotor wake/weapon interaction problems. To perform these tests, the helicopter model is equipped with scaled-down main rotor and fuselage models. The Mach-scaled model is driven by an hydraulic or electric motor located inside the model, and the total system is remotely controlled. The extensive instrumentation and data acquisition system of such a model provides valuable

data not only for model validation but also for the reduction of risks and time involved with weapon system installation programs. For this purpose dedicated test facilities have to be available that allow flexible adaptation to the specific problem under investigation. Moreover, procedures for the preparation, the conduction and the analysis of wind tunnel tests have to be developed in order to produce high quality and reliable data in a short time.

As an example for a powered aerodynamically and dynamically scaled helicopter model using a 4.2 m diameter rotor, Figure 24 shows the test rig of the German DLR equipped with the NH90 model of the Dutch NLR in the German/Dutch Wind Tunnel DNW. The main purpose of this test program in the 9.5 by 9.5 m closed test section of the DNW was primarily devoted to the low speed flight characteristics. An extensive data base with test results of various horizontal tail configurations was established, supporting the design of the horizontal tail and flight control system [Ref. 12]. In a second test program the model was installed in the open jet test section of the DNW, as shown in Figure 25. This campaign was primarily aimed at evaluating engine air intake characteristics, exhaust gas recirculation and infrared signature. Tests were performed at a wide range of forward, sideward and rearward flight conditions. A large number of parameters were measured, ranging from rotor hub loads, blade loads, and blade angles to air intake pressures and temperature distributions, and exhaust gas and fuselage skin temperatures [Ref. 13].

Figure 24: Powered model (1/4-scale) of NH90 in DNW

3.3 Flight Tests for Model Validation

The predictive capability of the mathematical model is determined by comparing the flight measured helicopter responses with those predicted by the model for the same control inputs.

The validation test data is an important part of flight simulator certification and acceptance. To eliminate subjective evaluation, the FAA has specified guidelines in terms of tolerances for each variable, depending upon the nature of the validation test. For example, in the case of short term

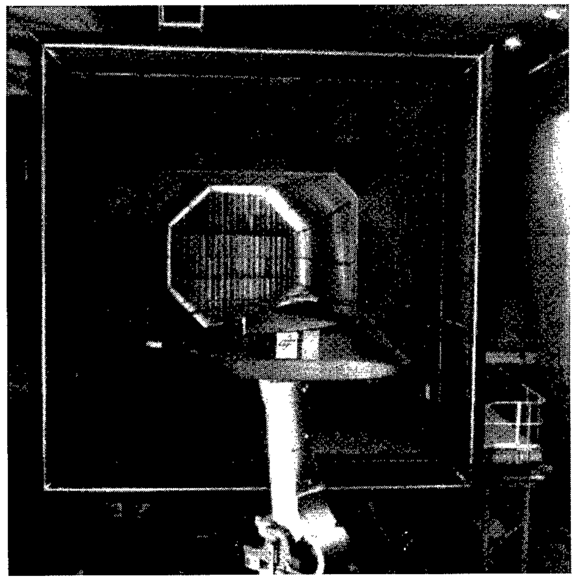


Figure 25: NH90 Model in open jet test section of DNW

response for dynamic stability the tolerances are ±1.5 degree pitch attitude or ±2 deg/s pitch rate and ±0.1 g for normal acceleration. This has to be demonstrated in cruise and climb flight conditions with two different airspeeds. The flight measurements with these tolerances define a band within which the model predicted response must lie to meet the specified accuracy requirements [Ref. 14]. Although the majority of the validation tests are verified in time domain either through time histories or in terms of period and damping ratios of the oscillatory modes such as phugoid or dutch roll, it is also possible to extend the verification to the frequency domain, which may bring out more clearly the range of applicability of the mathematical model. This is particularly important for high authority flight control systems. In this respect, rotorcraft system identification techniques are likely to become more significance for model validation in the future [Ref. 15].

In general, a big amount of flight tests is required to fully validate a mathematical model. The experiments may cover the following flight conditions:

- Trim conditions at different forward flight speeds with control inputs optimized for system identification purposes,
- Descending and climbing flight with control inputs in all axes,
- Curved flight with control inputs in all axes,
- Maximum amplitude pedal steps,
- Roll and pitch inputs with coupling compensation,
- Roll reversals,
- Decelerations,
- Approach and landing.

The helicopter instrumentation may include the following sensors depending on the specific model to be validated:

- Rate gyros for roll, pitch, and yaw rates,
- Vertical gyro for roll and pitch attitude, and a gyro for heading,
- Linear accelerometers, installed close to the helicopters CG to measure the longitudinal, lateral, and vertical accelerations,

- Potentiometers at each pilot's control (stick, pedals, collective lever) to measure the control inputs,
- Tachometer at the main rotor shaft for rpm,
- Helicopter air data system for speed measurements in the total speed range including hover,
- Rotor instrumentation for flapping, lead-lag, and blade pitch angles.

The data should be digitized and recorded on board of the helicopter. Depending on the signal frequency content the sampling rates should be high enough, e.g. 50 to 100 Hz. Due to the high vibration level, linear accelerations should bee sampled much higher, e.g. with 300 Hz. During the flight tests selected data should be send via telemetry to a ground station and processed in real-time in order to check for data compatibility and to allow for monitoring some of the critical data in extreme flight conditions [Ref. 16].

During offline processing all data have to be converted in engineering units, and filtered and corrected where necessary. Finally the time histories or the required parameters have to be calculated and presented as required for the model validation process.

4. Handling Qualities Criteria

4.1 Definitions

Handling qualities have been defined as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of the aircraft role". Thus, handling qualities may be thought of as being a measure of the degree to which the pilot, with acceptable workload and training, is able to exploit the aircraft's inherent potential. In order to quantify these characteristics, the Cooper-Harper pilot rating scale (Figure 26) was introduced and is now widely accepted as a measure of handling qualities [Ref. 17]. The scale is divided into three levels with task performance and pilot workload being the decisive factors. A pilot handling qualities rating is given for a specific aircraft configuration, flying a specific task under specific environmental conditions. With this statement in mind, it becomes obvious that the handing qualities of a helicopter/weapon system may be quite different compared to the handling qualities of a "clean" helicopter: the aircraft configuration has changed and often the mission has changed too. Therefore, in order to secure the desired task performance of the overall system, the evaluation of the handling qualities of a helicopter with a weapon system installed is of particular interest for the procuring agency.

The techniques and tools available for handling qualities evaluation of helicopters will remain the same for helicopter/weapon systems. In the following, main emphasis will be laid on those criteria where the biggest differences may be expected.

4.2 Structure of ADS-33 Handling Qualities Requirements

The most comprehensive set of handling qualities requirements is provided by the US Army's Aeronautical Design Standard ADS-33, with the latest version ADS-33D [Ref. 3]. These requirements were developed in the 1980s based on data provided by several NATO countries namely Canada (NAE, Ottawa), Germany (DLR, Braunschweig), UK (DRA, Bedford), and different organizations in the USA led by the US Army.

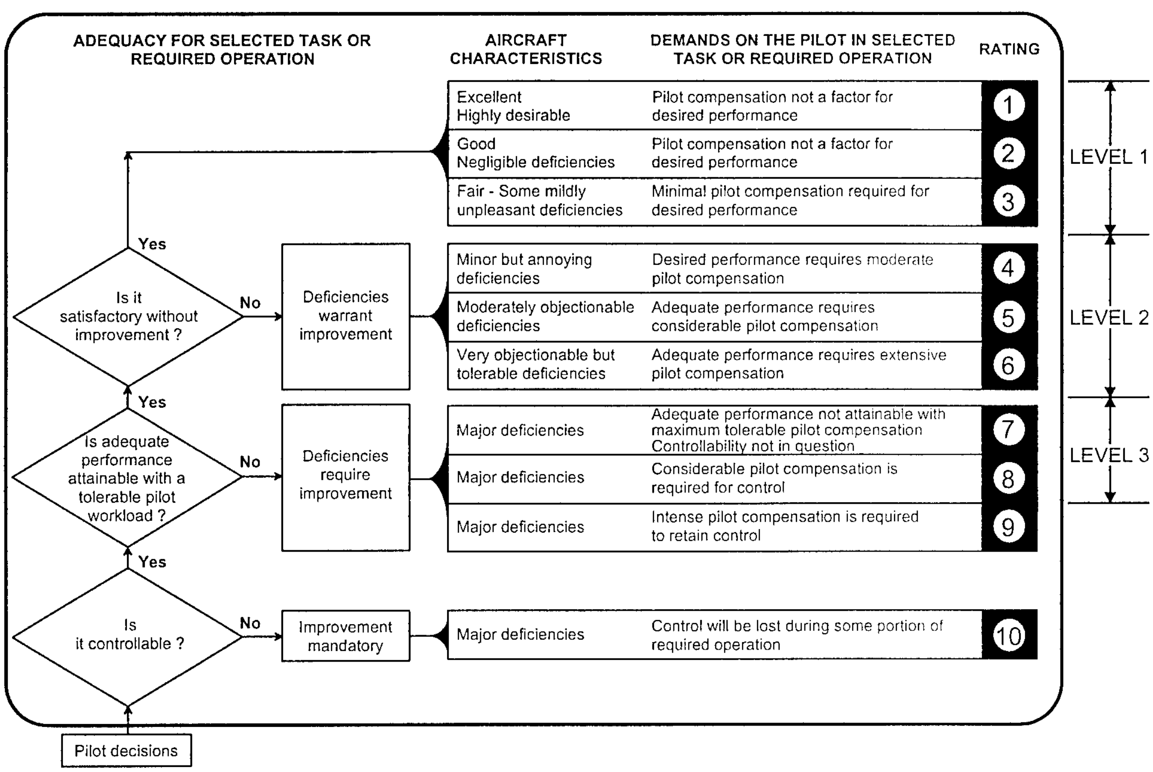


Figure 26: Handling qualities rating scale and definitions of handling qualities levels [Ref. 1]

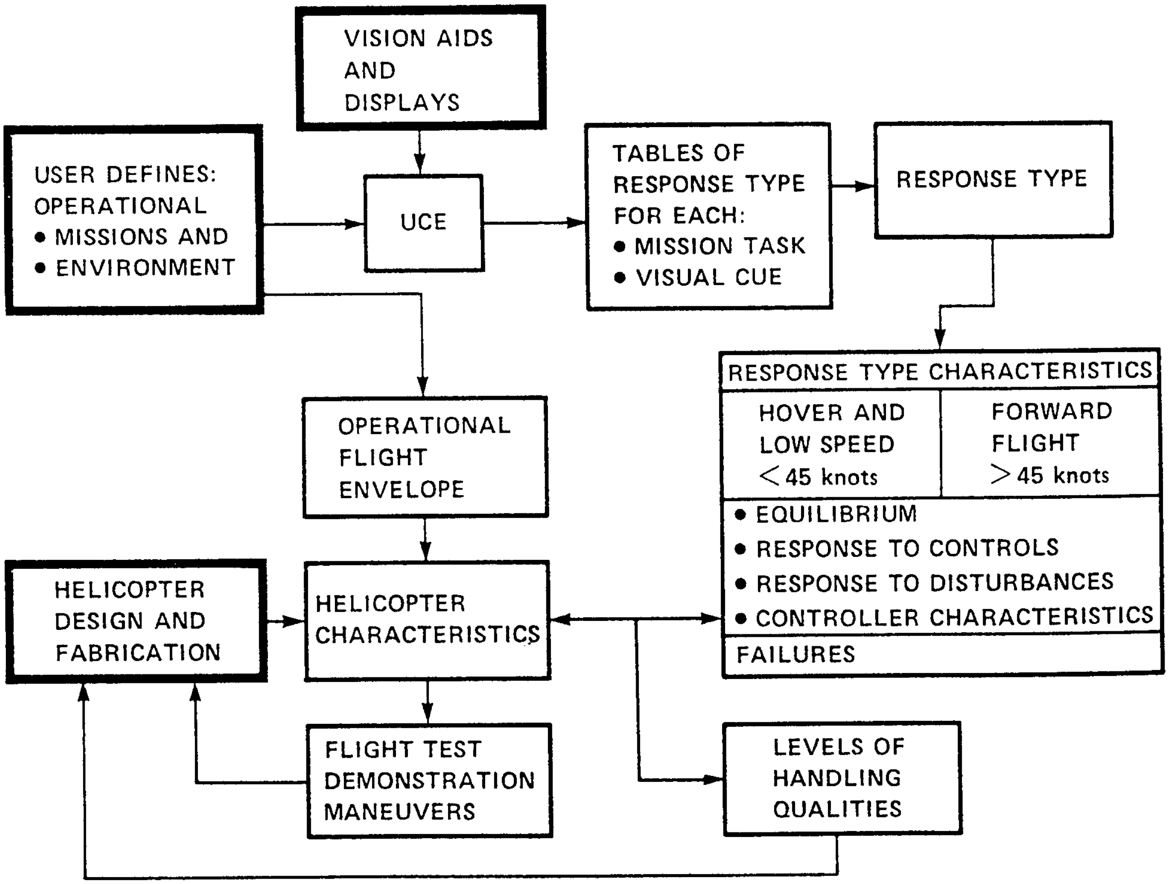


Figure 27: Schematic diagram for ADS-33 handling qualities specification

The structure of the ADS-33 is considerably different from earlier specifications, and several innovations have been introduced. Among those is the attempt to recognize and accommodate the effects of degraded visual cues resulting from the use of displays and vision aids at night and in poor weather conditions. The specification requires different response types and different response bandwidths for tasks performed with degraded visual cues. In this connection, the response type is defined as a characterization of the rotorcraft response to a control input in terms of well recognized stability augmentation systems, i.e. rate, rate command/attitude hold, etc. [Ref. 18].

A schematic of the ADS-33 structure is outlined in Figure 27, representing the intended method of use. The user of the helicopter system has to define the operational missions and environment [Ref. 1]. Based on this description the helicopter designer develops the flight envelopes and determines the required response types. Response type characteristics are defined for hover and low speed, and for forward flight. The level of handling qualities, as defined from the Cooper-Harper rating scale, is then determined by the comparison of the required response characteristics with those characteristics achieved by the helicopter throughout the flight envelopes. This comparison provides an analytical assessment of the level of handling qualities based on the criteria established in ADS-33.

The ultimate assessment of any aircraft is flight evaluation performing mission-related tasks. To address this directly ADS-33 provides a selection of flight test demonstration maneuvers that have to be performed with a specified level of performance. The flight test maneuvers represent demanding parts of the missions and correspond to mission task elements (MTE), which are used as handling qualities tasks for generating the mission-oriented data base for the criteria.

In Figure 28 this quantitative and qualitative handling qualities evaluation scheme is outlined. In general,it is expected that the handling qualities evaluation using the specified criteria corresponds with the evaluation on the basis of the relevant flight test maneuvers, provided a broad and adequate data base was available for the verification of the criteria. On the other side, it is recognized that the open-loop criteria are based on present knowledge and on a limited data base. Therefore, the comparison of qualitative and quantitative evaluation results may be seen as an opportunity to unveil deficiencies not covered by the quantitative criteria. Conversely, not meeting the quantitative requirements guarantees less than desirable handling qualities [Ref. 19].

For helicopters with external stores installed the ADS-33 provides the general statement: "The requirements of this specification shall apply for all combinations of external stores and slung loads required by the operational missions. The effects of external stores on the weight, moments of inertia, center-of-gravity position, and aerodynamic characteristics of the rotorcraft shall be considered for each Mission-Task-Element. When the stores contain expendable loads, the requirements of this specification apply throughout the range of store loadings."

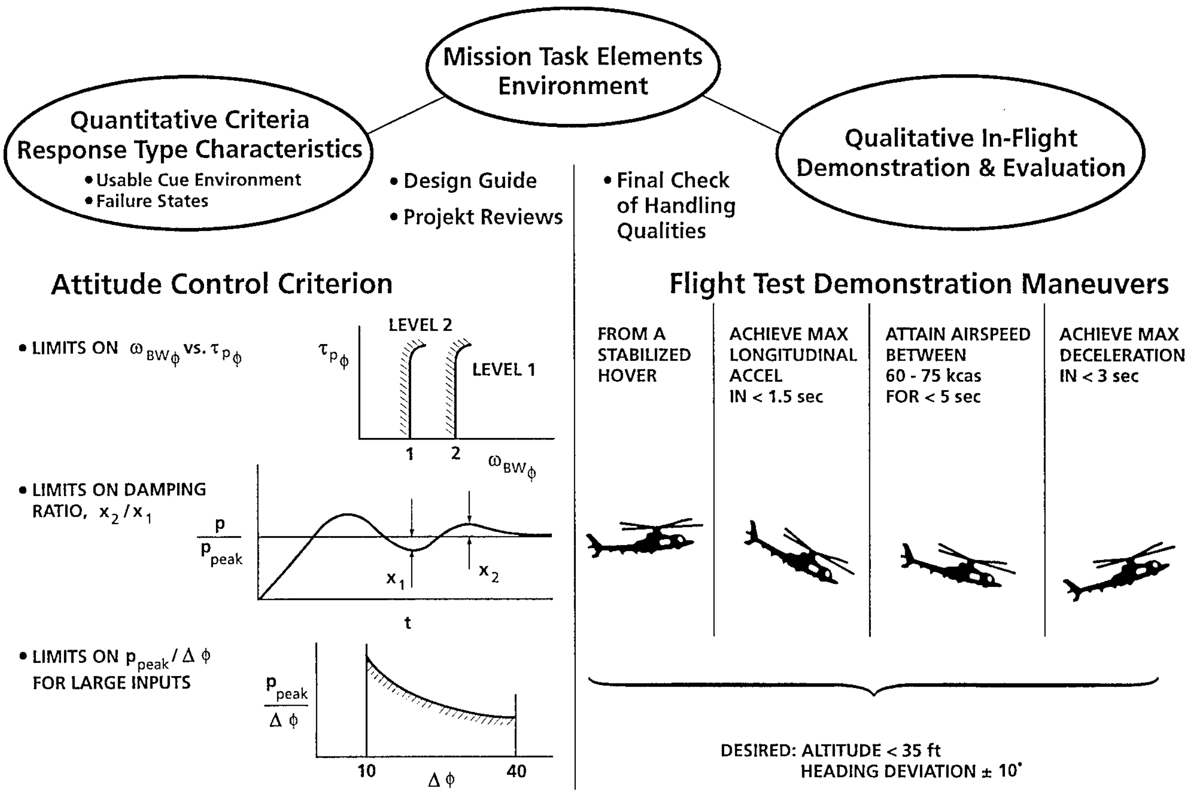


Figure 28: Quantitative and qualitative handling qualities evaluation

4.3 Quantitative Criteria

The ADS-33 is a mission-oriented specification, based on the mission task elements and the cueing available to the pilot. Minimum requirements are established for control response types and their characteristics. These requirements are categorized in terms of small, moderate, and large amplitude attitude changes (Figure 29) and are defined for comparison with the rotorcraft characteristics [Ref. 20].

The small amplitude response requirements include both short-term and mid-term responses where the short-term response refers to the rotorcraft characteristics in pilot tasks such as closed-loop, compensatory tracking and the mid-term response criteria are intended to ensure good handling qualities when less precise maneuvering is required. The requirements for the short-term response are specified in terms of a frequency based criterion called bandwidth. The frequency response data required to measure the bandwidth parameters are defined in Figure 30. The bandwidth, ω_{BW}, is measured from a frequency response (Bode) plot of the rotorcraft angular attitude response to the cockpit controller input and must include all the elements in the flight control system. Generally, a good system will have a high bandwidth and a poor system will have a low bandwidth. The bandwidth criterion is an application of the crossover model concept. It is based on the premise that the maximum crossover frequency that a pure gain pilot can achieve, without threatening the stability, is a valid figure-of-merit of the controlled element. Physically, low values of bandwidth indicate a need for pilot lead equalization to achieve the required mission performance. Excessive demands for pilot lead equalization have been shown to result in degraded handling qualities ratings. The efforts to develop bandwidth as a generalized criterion for highly augmented aircraft have shown that the pilots were also sensitive to the shape of the phase curve at frequencies beyond the neutral stability frequency, ω_{180}. This is addressed by the phase delay parameter, τ_p. Large values of phase delay can arise from many sources, among which are the high order rotor response, control actuator dynamics, filters, and computational time delays. An aircraft with a large phase delay may be prone to aircraft-pilot coupling (APC) [Ref. 21].

As previously stated, ADS-33 is a mission-oriented handling qualities specification and hence, the control response requirements are a function of the degree of divided attention, the visual environment, and the aggressiveness demanded in the mission task element (MTE). The forward flight (> 45 knots) bandwidth criteria for the roll axis are shown in Figure 31. Three sets of limits are specified: the more stringent limits apply to the air combat MTEs and the more relaxed boundaries cover all other MTEs. For divided attention operations (specifically IMC flight), the more relaxed bandwidth values are combined with the more stringent phase delay requirements [Ref. 22].

The necessary frequency response data for extracting the bandwidth can be obtained from carefully designed flight tests. The flight test procedure consists of performing manual or automated frequency sweeps in each axis at the tested flight condition (Figure 32). The data are analyzed using fast Fourier transform methods. A typical transfer function is shown in Figure 33 for the BO 105 helicopter [Ref. 23].

The mid-term response for small-amplitude attitude changes is specified in terms of frequency and damping of characteristic oscillations. Figure 34 shows the limits on pitch and roll oscillations for fully attended operations in hover and low speed.

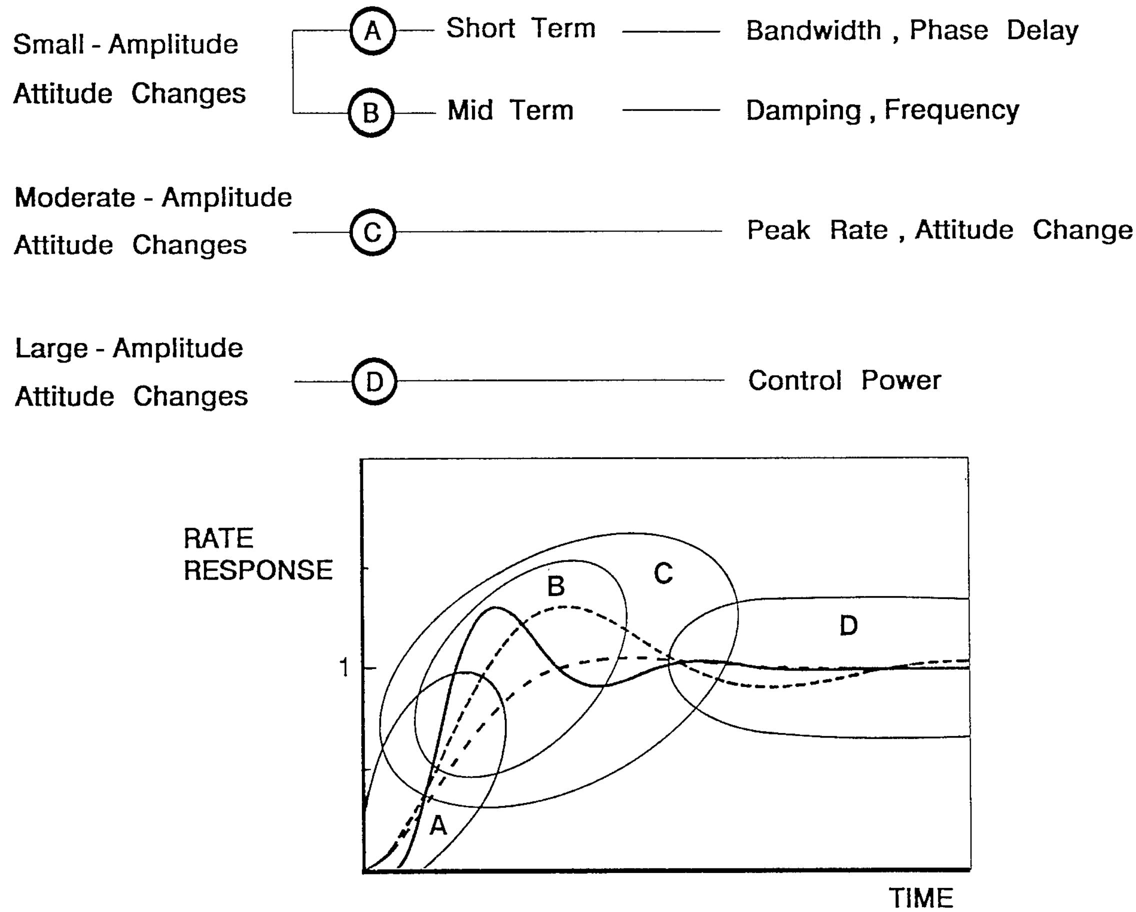


Figure 29: Classification of dynamic response criteria

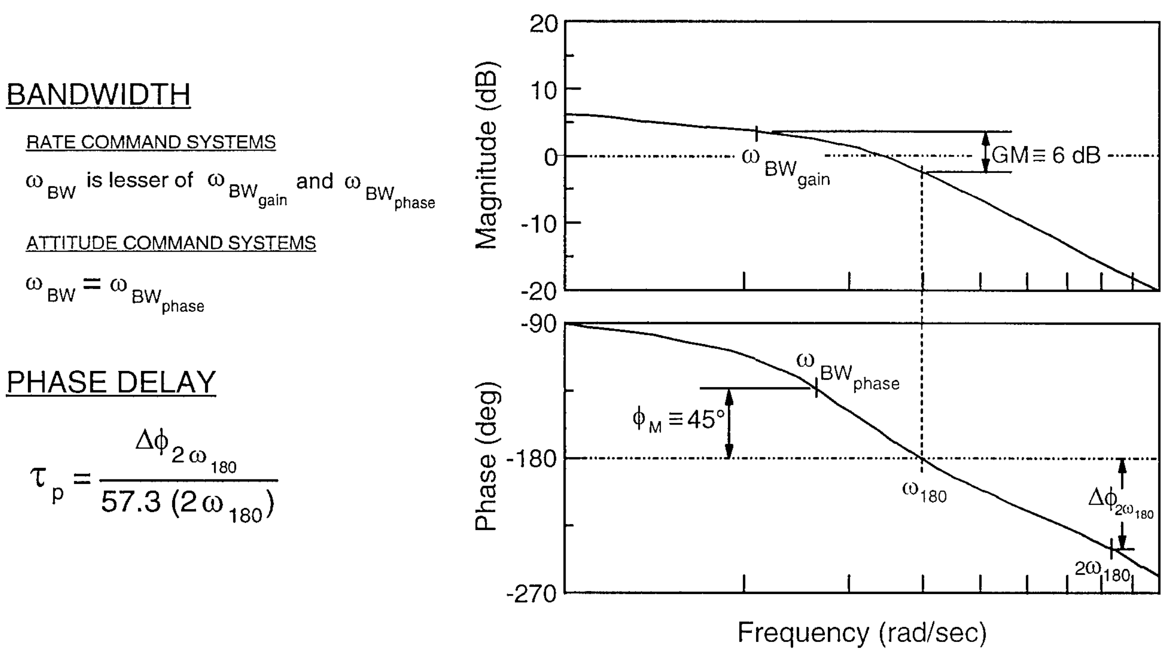


Figure 30: Definition of bandwidth and phase delay

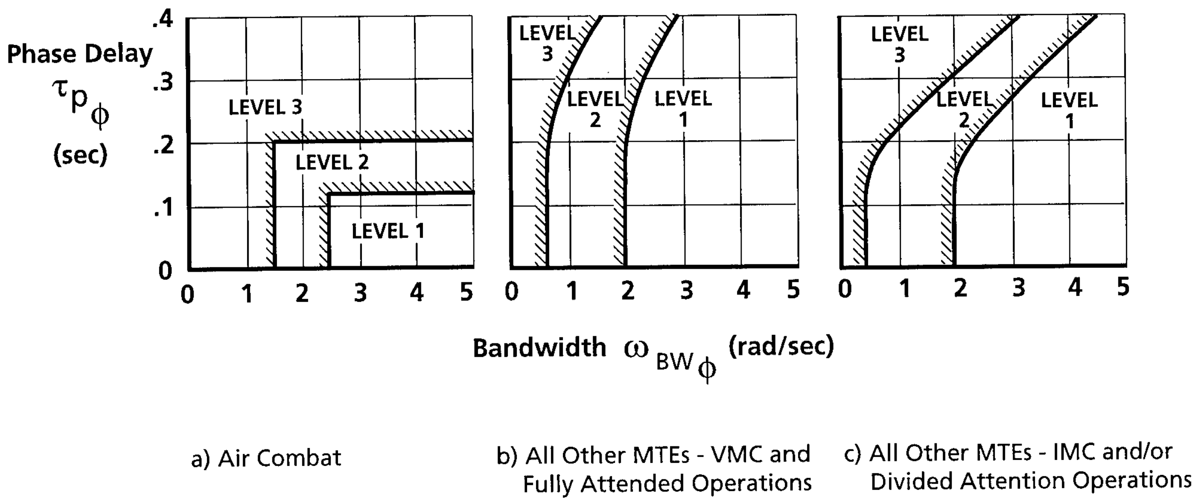


Figure 31 Requirements for small-amplitude roll attitude changes - forward flight [Ref. 3]

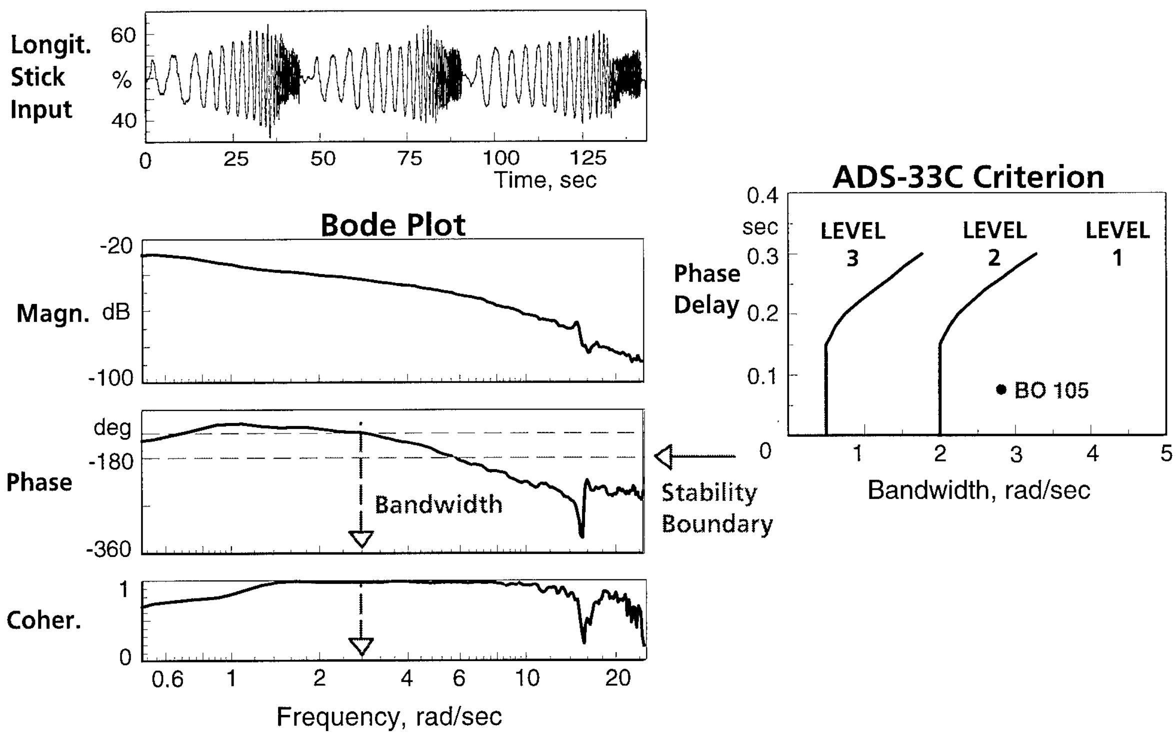


Figure 32: Frequency sweeps and determination of bandwidth and phase delay

The requirement for moderate-amplitude attitude changes for the roll axis in forward flight is shown in Figure 35. The parameter Peak Angular Rate / Peak Attitude Change $P_{pk}/\Delta\varnothing_{pk}$ represents a change in roll attitude from one steady value to another, to be accomplished as rapidly as possible. The initial attitude and the attitude change should be representative for the required MTE. The parameter can be analytically shown to be directly related to bandwidth, so that the criterion effectively allows decreasing bandwidth with increasingly large maneuvers.

The requirements for large-amplitude attitude changes are intended to be a measure of control power, and are specified herein as lower limits on the maximum steady angular rate or attitude that can be achieved with full control deflection in the cockpit. The criterion is divided into different levels of aggressiveness corresponding to the needs of the missions. As an example, Figure 36 presents the requirements for large-amplitude roll attitude changes in forward flight.

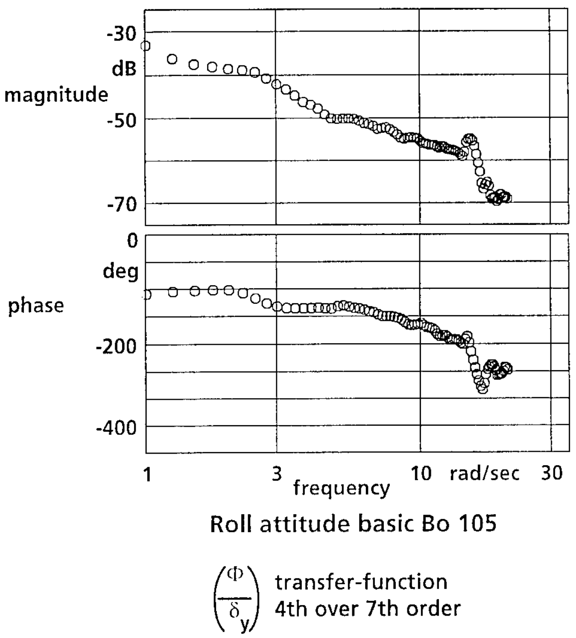


Figure 33: Transfer function for roll attitude of BO 105 helicopter

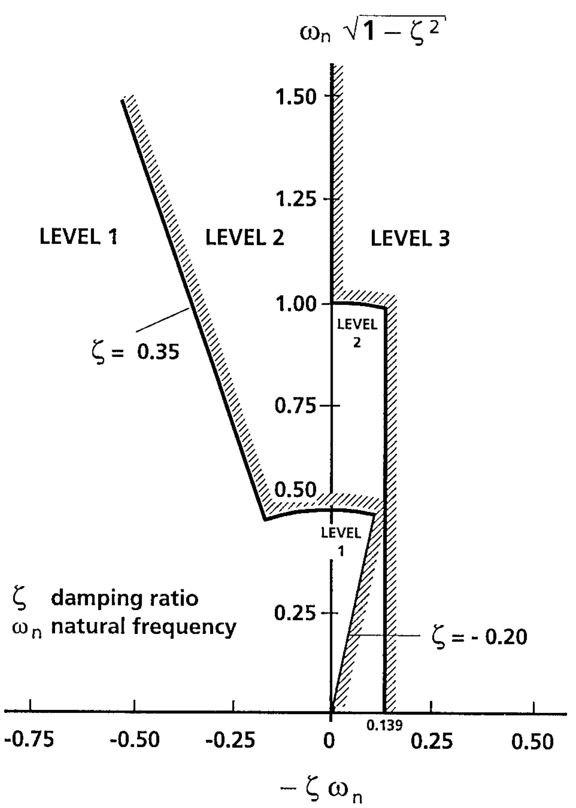


Figure 34: Limits on pitch and roll oscillations for fully attended operations - hover and low speed [Ref.3 [

As single rotor helicopters are inherently cross-coupled in response to controls and disturbances, interaxis coupling can be a significant factor especially in aggressive maneuvering tasks. The specification provides an overall qualitative requirement stating that "control to achieve a response in one axis shall not cause objectionable response in any one or more other axes". In addition, specific criteria are provided for roll due to pitch, pitch due to roll, and yaw due to collective control inputs. These criteria are still under discussion and new formats have been proposed recently [Ref. 24].

Other criteria, not discussed here, include the characteristics of collective control response, thrust margins, response to disturbances etc. These criteria, although critical in some cases where weapon systems have to be installed, are straightforward in understanding and application for integrated helicopter/weapon systems. In summary, it needs about 70 parameters to characterize the handling qualities of a helicopter even in simple terms. For a weapon system integration program it is therefore indispensable to carefully investigate the expected differences between the "clean" helicopter and the helicopter/weapon system by analytical tools, in order to avoid extensive flight testing for the quantitative evaluation. Flight testing should be concentrated on the essential parameters and on the qualitative evaluation based on the experience with analytical models or ground-based simulation.

4.4 Qualitative Evaluation

As mentioned above, a selection of flight test maneuvers is specified and included as an integral part of ADS-33 in order to provide an overall assessment of the helicopter's ability to perform certain critical tasks. The maneuvers correspond to the mission task elements which are used for the quantitative evaluations. Only those maneuvers required by the procuring agency have to be accomplished for compliance testing. The demonstration maneuvers shall be accomplished by at least three pilots which shall assign subjective ratings using the Cooper-Harper handling qualities rating scale. For level 1 handling qualities, as required in the operational flight envelope, the arithmetic average of the ratings shall be 3.5 or better. When operating in the service flight envelope a rating of 6.5 or better is required.

The use of the Cooper-Harper handling qualities ratings requires the definition of numerical values for desired and adequate task performance. These performance limits are set primarily to drive the level of aggressiveness and precision to which the maneuver is to be performed. Compliance with the performance standards may be measured subjectively form the cockpit or by the use of ground observers. It is not necessary to utilize complex instrumentation for these measurements.

The ADS-33D contains definitions for precision tasks in good visual environment including hover, hovering turn, landing, pirouette, and slope landing. As aggressive tasks in good visual environment the tasks turn to target, vertical remask, acceleration and deceleration, sidestep, slalom, deceleration to dash, transient turn, pullup / pushover, roll reversal at reduced and elevated load factors, high yo-yo, low yo-yo are described. Decelerating approach in IMC conditions, precision tasks and moderately aggressive tasks in the degraded visual environment complete the flight test maneuvers specified in ADS-33D.

As an example Figure 37 shows the suggested course for the slalom maneuver as an aggressive task in good visual environment [Ref. 3]. The objectives of this task are:

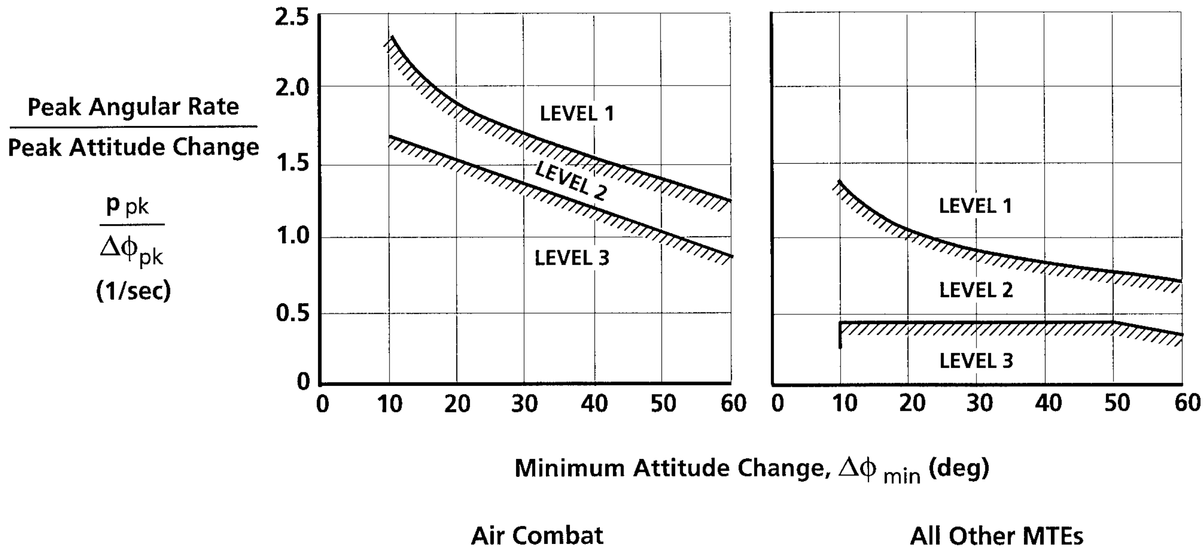


Figure 35: Roll response limits for moderate-amplitude roll attitude changes - forward speed [Ref. 3]

MISSION-TASK ELEMENT (MTE)	RATE RESPONSE-TYPES: MINIMUM ACHIEVABLE ROLL RATE (deg/sec)		ATTITUDE RESPONSE-TYPES: MINIMUM ACHIEVABLE BANK ANGLE (deg)	
	LEVEL 1	LEVEL 2	LEVEL 1	LEVEL 2
LIMITED MANEUVERING				
All MTEs not otherwise specified	30	15	25	15
IMC MTEs	15	12	25	15
AGGRESSIVE MANEUVERING				
Ground Attack, Slalom, Pull-Up/Push-Over, Assault Landing	50	21	90	30
Air Combat	90	50	Unlimited	60

Figure 36: Requirements for large-amplitude roll attitude changes [Ref. 3]

- Check ability to maneuver aggressively in forward flight and with respect to objects on the ground,
- Check turn coordination for aggressive forward flight maneuvering,
- Check for objectionable interaxis coupling during aggressive forward flight maneuvering.

The ADS-33D includes detailed descriptions of the maneuver and of the test course, and specifies the desired task performance:

- Maintain an airspeed of at least 60 knots throughout the course.

The adequate task performance for the slalom maneuver is defined as:

- Maintain an airspeed of at least 40 knots throughout the course.

With the same description of the maneuver and of the test course this task is used as moderately aggressive task in the degraded visual environment. In this case the desired task performance is relaxed down to at least 30 knots airspeed, and the adequate performance to at least 15 knots.

It should be mentioned that the purpose of these maneuvers is to check the handling qualities at the most critical or demanding flight conditions and loadings from the standpoint of controllability, not from that of the performance of the helicopter.

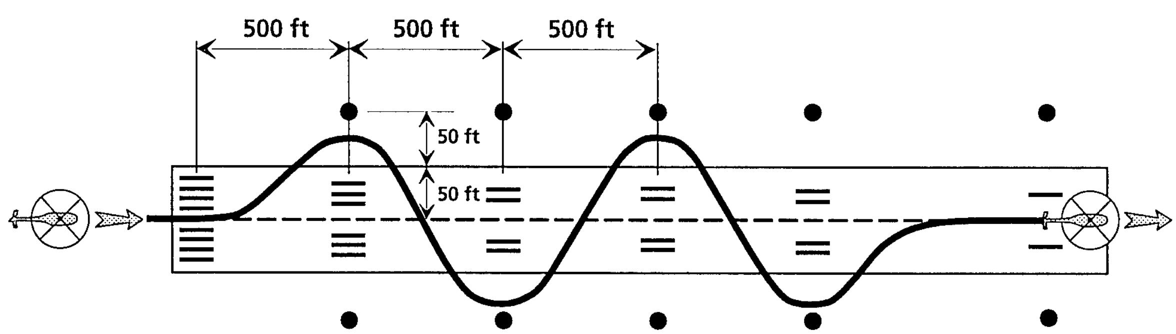


Figure 37: Suggested course for slalom maneuver [Ref. 3]

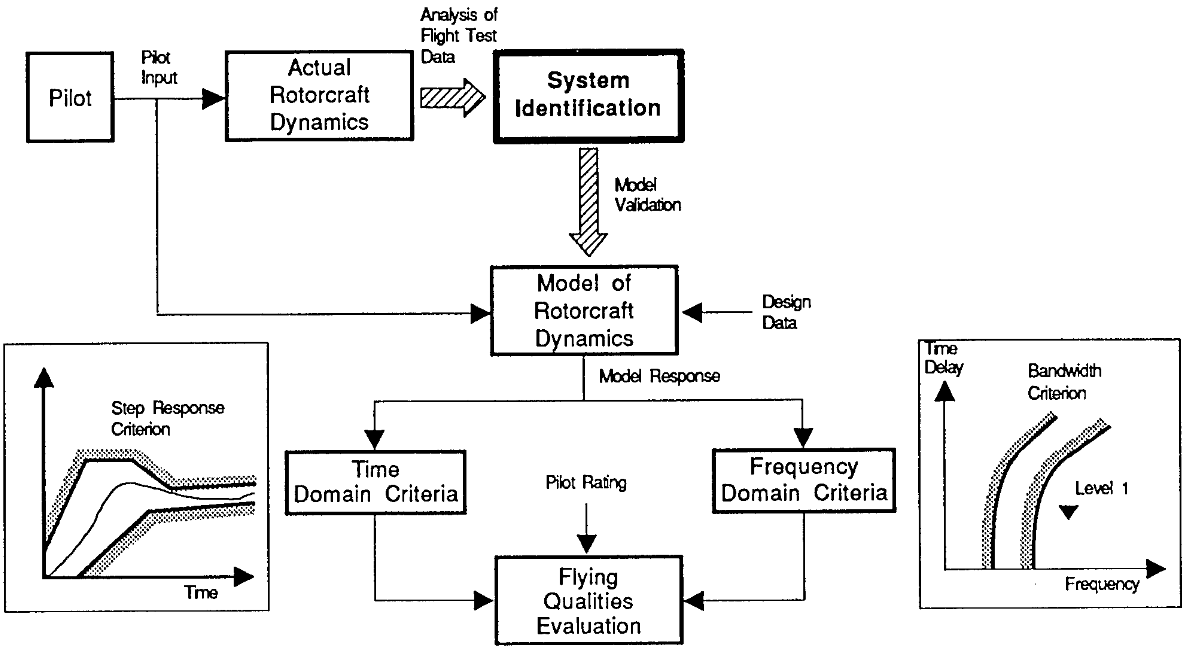


Figure 38: System identification for rotorcraft flying qualities evaluation [Ref. 7]

5. Handling Qualities Flight Testing

Handling qualities evaluations by flight testing are conducted quantitatively via open-loop testing and qualitatively via closed-loop testing. Whereas closed-loop testing produces direct assessments via pilots' Cooper-Harper handling qualities ratings, the objective of open-loop testing is system identification [Ref. 25].

Rotorcraft system identification is a methodology by which a mathematical model description of the dynamic characteristics of the helicopter are extracted from flight data. System identification and determining the associated relationship to rotorcraft handling qualities have been a difficult task to accomplish for the flight test community. Classic handling qualities analysis techniques primarily involve time history analysis of vehicle response to certain control inputs such as steps, impulses, and doublet. The results of this analysis are parameters like rise time, time constants, time-to-double/half amplitude, natural frequencies, and damping ratios. As discussed above, modern handling qualities specifications, specifically ADS-33, have been derived mainly from frequency domain databases and require the determination of parameters like magnitude and phase bandwidth from the frequency response derived from flight data. Procedures for obtaining pilot-generated frequency sweep data, processing and reducing the frequency response data,and for data analysis have been developed and refined in recent years [Refs. 26, 27]. Therefore, system identification will play in future a major role in the rotorcraft open-loop testing, i.e. the determination of quantitative parameters from flight data (Figure 38). Seen from the aspect of cost effectiveness important benefits of rotorcraft system identification are related to the potential to reduce the amount of costly and time-consuming flight testing with respect to specification and certification requirements. Improved assessment and evaluation of handling qualities parameters becomes possible by this approach [Ref. 7].

No attempt is made here to describe the procedures and techniques available for handling qualities flight testing in detail; the reader is referred to comprehensive reviews of the subject [Ref. 28, 29, 30]. A paper recently published in AGARD-CP-592 [Ref. 31] provides extensive insight in ADS-33 flight testing using a specific helicopter, the BO 105. The evaluation addressed both the quantitative and the qualitative ADS-33 criteria. The conclusions from this major effort, including more than 80 hours of flight testing, support the overall philosophy of the specification and present valuable recommendations with respect to the individual criteria and demonstration maneuvers.

The installations of external weapons produce aerodynamic effects on the airframe, modify mass distribution and inertia characteristics of the helicopter, and affect the helicopter's behavior during store release and weapon delivery. As a consequence, the armed helicopter has to be flight tested in order to evaluate the deterioration of some handling qualities parameters in respect to those of the "clean" vehicle, and to prove the compliance with the applicable requirements. The handling qualities specification ADS-33 provides a sound basis to guarantee good handling qualities of the helicopter with the weapon system installed in the total operational flight envelope.

6. Conclusion

This lecture discusses the fundamental tools for handling qualities evaluation of helicopters with weapon systems installed.

- Reliable nonlinear and linear analytical models including the main influences of the weapon system to be integrated, represent the basis for trustworthy handling qualities studies prior to the integration.
- Systematic approaches to validate the mathematical models yield the level of fidelity required for the actual application of the model under consideration.

- The validation process of a flightdynamics model needs dedicated and reliable data bases generated by wind tunnel and flight testing. For this purpose data of both configurations, the "clean" helicopter and the helicopter/weapon system are required for consideration of the interference effects.
- The techniques and tools available for handling qualities evaluation of helicopters will remain the same for helicopter/weapon systems.
- Recent and extensive experience demonstrates that ADS-33D Handling Qualities Requirements for Military Rotorcraft provide a sound basis to guarantee the required task performance of the helicopter, with the weapon system installed, in the total operational flight envelope.

7. References

[1] Key, D.L., "A New Qualities Specification for U.S. Military Rotorcraft" in "Helicopter Handling Qualities and Control", The Royal Aeronautical Society, London, November 1988, Paper 3.

[2] Padfield, G.D., "Helicopter Flight Dynamics", Blackwell Science Ltd, Oxford, UK, 1996 (ISBN 0-632-03248-0)

[3] US Army Aviation and Troop Command, "Handling Qualities Requirements for Military Rotorcraft", Aeronautical Design Standard ADS-33D-PRF, St.Louis (MO), USA, 1996.

[4] "Integration of Externally Carried Weapon Systems with Military Helicopters", AGARD-AR-247, 1990.

[5] Schrage, D., "Review of Recent System Identification Activities", in AGARD-AR-280, 1991, Chapter 3.

[6] von Grünhagen, W., "Dynamic Inflow Modelling for Helicopter Rotors and its Influence on the Prediction of Crosscoupling", in "2nd International Aeromechanics Specialists' Conference", American Helicopter Society, Bridgeport (Connecticut), USA, 1995.

[7] Hamel, P.G., "Introduction and Overview", in "Rotorcraft System Identification", AGARD-AR-280, 1991, Chapter 1.

[8] Kaletka, J., "Identification Results, Case Study II: BO 105", in "Rotorcraft System Identification", AGARD-AR-280, 1991, Chapter 6.

[9] US Department of Transportation, Federal Aviation Administration, "Helicopter Simulator Qualification", FAA Advisory Circular AC 120-63, 1994.

[10] Gray, G.J. and von Grünhagen, W., "An Investigation of Open Loop and Inverse Simulation as Nonlinear Model Validation Tools for Helicopter Flight Mechanics", in "Rotorcraft Simulation", The Royal Aeronautical Society, London, May 1994.

[11] Gmelin, B.L., "Rotorcraft Activities in the European Research Establishments (DLR, DRA, NLR, ONERA)", in "20th European Rotorcraft Forum", Amsterdam, October 1994.

[12] Phelps, K., "AHS Technical Committee Highlights, Test & Evaluation", Vertiflite Vol. 42, No. 3, May/June 1996.

[13] "NLR Tests New Powered NH90 Helicopter Model in German-Dutch Wind Tunnel", NLR News, No. 25, January 1997.

[14] Hamel, P.G. and Jategaonkar, R.V., "Evolution of Flight Vehicle System Identification", Journal of Aircraft, Vol. 33, No. 1, 1996.

[15] Hamel, P.G. et al., "Rotorcraft System Identification", AGARD-LS-178, October 1991.

[16] Kaletka, J., "Instrumentation and Data Processing", in "Rotorcraft System Identification", AGARD-LS-178 October 1991.

[17] Cooper, G.E. and Harper, R.P. Jr., "The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities", NASA TM D-5133, 1969.

[18] Key, D.L. and Hoh, R.E., "New Handling - Qualities Requirements and How They Can Be Met", in "43rd Annual National Forum", American Helicopter Society, St.Louis (Mo), USA, May 1987.

[19] Gmelin, B.L. and Pausder, H.-J., "Mission Requirements and Handling Qualities" in "Helicopter Aeromechanics", AGARD-LS-139, April 1985.

[20] Gmelin, B.L. and Pausder, H.-J., "Test Techniques for Helicopter Handling Qualities Evaluation and Design", in "Helicopter Handling Qualities and Control", The Royal Aeronautical Society, London, November 1988, Paper 22.

[21] Hamel, P.G., "Rotorcraft-Pilot Coupling, A Critical Issue for Highly Augmented Helicopters?" in "Advanced in Rotorcraft Technology", AGARD-CP-592, 1996, Paper 21.

[22] Pausder, H.-J. and Blanken, C.L., "Investigation of the Effects of Bandwidth and Time Delay on Helicopter Roll-Axis Handling Qualities" in "18th European Rotorcraft Forum", Avignon, France, September 1992.

[23] von Grünhagen, W. et al., "A High Bandwidth Control System for the Helicopter In-Flight Simulator ATTHeS-Modelling, Performance and Applications", in "Advances in Aircraft Flight Control (Editor: M.B. Tischler)", Taylor & Francis, 1996 (ISBN 0 7484 04791), pp. 73 - 101.

[24] Ockier, C.J., Pausder, H.-J. and Blanken, C.L., "An Investigation of the Effects of Pitch-Roll (De)Coupling on Helicopter Handling Qualities", DLR FB 95-08, Febr. 1995 (Also: NASA TM 110349).

[25] Tischler, M.B., "System Identification Requirements for High Bandwidth Rotorcraft Flight Control System Design", in "Rotorcraft System Identification", AGARD-LS-178, October 1991.

[26] Tischler, M.B., "Demonstration of Frequency Domain Testing Technique Using a Bell 214ST Helicopter", NASA TM 89422, April 1987.

[27] Kolwey, H.G., "The New ADS-33 Process: Cautions for Implementation", Journal of the American Helicopter Society, Vol. 41, No. 1, January 1996, pp. 3 - 6.

[28] Padfield, G.D., "Flight Testing for Performance and Flying Qualities", in "Helicopter Aeromechanics", AGARD-LS-139, April 1985.

[29] Williams, J.N., Ham, J.A. and Tischler, M.B., "Flight Test Manual, Rotorcraft Frequency Domain Flight Testing", US Army Aviation Technical Test Center, September 1995.

[30] Ockier, C.J. and Pausder, H.-J., "Experiences with ADS-33 Helicopter Specification Testing and Contributions to Refinement Research", in "Active Control Technology: Applications and Lessons Learned", AGARD-CP-560, January 1995.

[31] Ockier, C.J. and Gollnick, V., "ADS-33 Flight Testing - Lessons Learned", in "Advances in Rotorcraft Technology", AGARD-CP-592, Paper 10, May 1996.

STORE SEPARATION

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SUMMARY

The safe separation of a store from any aircraft represents potentially the most hazardous phase of the store release process.

The paper examines in turn the various mechanical and aerodynamic influences that come into play during store separation, reviews the requirements imposed by national standards, and explores how modelling and instrumentation techniques have advanced to benefit programmes that include verification of safe store separation.

LIST OF ACRONYMS

AGL	Above Ground Level
ASL	Above Sea Level
ASuW	Anti Surface Warfare
ASW	Anti Submarine Warfare
fps	Feet Per Second
HERO	Hazards of Electromagnetic Radiation to Ordnance
IAS	Indicated Air Speed
KTAS	Knots True Air Speed

1. INTRODUCTION

The separation of a store from an aircraft represents an irrevocable and (Figure 1) highly visible step in that aircraft's mission. It cannot take place before the successful completion by the aircraft's avionic and hardware systems of an extensive series of processing, verification and authorisation stages. The aircrew hold the ultimate sanction in that they may halt proceedings at any intermediate point, or else not sanction the actual separation. Despite all this, the process of store separation is potentially one of the most hazardous activities in which an aircraft can engage: for a short period of time it will be in very close proximity to a body that is unguided (for all practical purposes, in this context), may be dynamically highly mobile, and may be at least slightly unstable. This situation does attract the attention of aircrew, who naturally do not like to embark on a mission without all possible reassurances that all will go well. Extensive research work has been performed over many years to allow such reassurances to be given to fixed wing operators. It is no surprise to find that the rotary wing situation has been less tractable: although store separation airspeeds are much lower, their extent from the hover to airspeeds approaching 200 knots covers a much wider band of dynamic behaviour, especially when the helicopter's abilities to fly laterally and to the rear are factored in. There is also the interesting matter of rotor downwash to consider.

The purpose of this paper is to review the design, analysis, ground and flight test methods that currently stand behind the establishment of the separation characteristics of stores from helicopters.

2. TYPES OF STORE, AND OF STORE SEPARATION

It is worth spending a brief period to define a few terms for the purposes of this paper.

2.1 Store

A 'store' is usually regarded as anything that may be released deliberately from an aircraft, whether purely under gravitational action or with the assistance of one or more ejection forces. In practical terms this covers a very broad range of: rail-, tube- and drop-launched missiles, unguided rockets, and their launchers; gun and cannon projectiles, and the pods in which the guns or cannons may be installed; active countermeasure payloads; drop stores such as sonobuoys; external fuel tanks; and releasable sensor pods.

Some stores produce motor efflux plume effects and solid debris of appreciable size and mass when they separate from an aircraft. Plume effects include temperature, blast, flame, and combustion gases and particles. Depending on the nature of the store, the debris might include: spent boost motors; cartridge links; portions of protective store fairings; release or arming lanyards; and other disposable items of hardware that do not subsequently remain with the store. Such efflux and debris, which may have a significant effect on the aircraft's safety and on its ability to perform its mission effectively, are not included here as part of the store separation process, but are included among the aspects discussed elsewhere in this Lecture Series.

2.2 Separation

A satisfactory 'separation' may be defined as the establishment of the store in question in a trajectory away from the launch aircraft that does not endanger that aircraft, or impede the future intended functionality of performance of either the aircraft or the store for a defined aircraft flight envelope which may be a subset of the full flight envelope.

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This concern for the future wellbeing of the store and aircraft highlights a valuable point. 'Separation' of a store is often equated to its 'release', which is a convenient catch-all term that does not distinguish between the three very different types of separation that occur: firing, release (as such), and jettison.

2.2.1 Firing

Stores that are 'fired' are expelled from the aircraft in a direction that is almost always nearly horizontal and forwards relative to aircraft axes. The most common exceptions are active countermeasure payloads and crew-served weapons (Figure 2), whose principal firing axes are more lateral than longitudinal. Turret-mounted weapons are another obvious, although less common, exception to the axial-firing norm. Firing is conducted under controlled aircraft flying conditions that are delineated by a firing envelope, the ultimate objective being to deliver the store onto its target and not just to ensure its safe separation from the aircraft. The firing envelope should, ideally, extend throughout the aircraft's normal flight envelope; however aircraft and store system functionality considerations usually exclude areas of the flight envelope in the pursuit of the goal of optimising the probability of hitting the target (or, in the Anti Submarine Warfare (ASW) context, the splashpoint). Safety considerations, usually dictated by aircraft dynamic and aerodynamic factors but often also driven by the special effects mentioned earlier, impose further limitations. The more advanced helicopters automate these safety and operational firing constraints within their fire control systems, to reduce aircrew workload; operational constraints may be overridden, but not safety constraints.

In reality only certain areas of the operational firing envelope are used, as dictated by the operator's tactical doctrine, aircrew habit and the facilities provided by the aircraft's fire control system (Figure 3).

2.2.2 Release

Defining 'release' is simple, in that it covers much the same ground as 'firing' except that the store is of such a nature that it departs downwards instead of approximately horizontally. There is an arbitrary and slightly woolly dividing line that suggests that land based helicopters engaged in military operations fire their stores, as do naval helicopters engaged in missions of an equivalent type, such as amphibious support and armed policing. The stores deployed in a purely naval context are almost always released; this reflects the larger size of these stores, such as torpedoes, depth charges and missiles.

A store may be released under gravity or by ejection, depending on the nature of the store and on its installation on the aircraft. Several helicopter manufacturers tend to avoid ejecting stores if possible, to simplify rearming, to minimise release reaction loads back into airframe structure, and to eliminate one possible source of Hazards of Electromagnetic Radiation to Ordnance (HERO) problems if the helicopter is to operate on board ships. This would be heresy in the fixed wing world, but the lower aerodynamic loads on the helicopter-released store at least allow this to be treated as an option. However store release by ejection may be essential in some cases. For example to ensure that an Anti Surface Warfare (ASuW) anti-ship missile, once it has fallen clear of the aircraft, lies within the required pitch attitude envelope at the moment of boost motor ignition, or to ensure that a store is projected laterally sufficiently to clear a skidded undercarriage. Figure 4 illustrates a mismatch in predicted, as opposed to required, store attitude at boost motor ignition. This situation emerged during analysis early on in the programme in question, and was resolved successfully by adjusting the balance of forces on the store produced by the ejector release unit - an option that would not have been open if gravity release had been specified.

2.2.3 Jettison

Helicopter manufacturers continue to grumble about the excessive aerodynamic drag imposed by empty launchers. Despite this, helicopter operators have yet to adopt the fairly widespread fixed wing practice of minimising parasitic drag by jettisoning empty launchers - especially rocket launchers, whose relatively low cost would help to justify this approach - as soon as their payloads have been expended. Thus helicopter jettison is essentially reserved for emergency situations, in which the aircrew need to reduce aircraft All Up Weight immediately or else to dispose of an individual store that has entered a dangerous condition.

Jettison would be an identical stores separation process to that of release, were it not for three important differences: firstly, it applies to all externally mounted stores, although externally mounted stores that are fired as munitions are jettisoned as a unit with their launcher - with the inevitable exceptions that will be mentioned later; secondly, there is no real interest in the progress of the store, regardless of its operational function, once it has safely cleared the aircraft; and thirdly, jettison should be possible throughout the aircraft's full flight envelope.

Instances of emergency jettison are liable to occur when the helicopter is in steep descent or in autorotation, when fuselage attitudes and angles of attack are at their greatest.

The military aviation community is feeling its way, very carefully one might consider, towards providing at least its attack helicopters with an air-to-air missile self-defence capability. Two factors that influence this apparent caution are the understandable reluctance to give up existing store stations to this new function, and the conflicting but equally forceful driver to possess an air-to-air capability for use in any armed mission at any time. For most helicopters the answer is unpalatable, in that the helicopter's geometry

and payload rule out air-to-air missiles other than as an alternative role fit. Only the larger, more powerful helicopters can accommodate the extra store stations, almost always mounted on the weapon carrier wingtips (Figure 5). This requires air-to-air missile launchers to be jettisoned in a lateral direction, rather than downwards as is usual, and introduces an altogether new set of aerodynamic conditions.

Finally we come to the exceptions mentioned above: certain munition stores that are jettisoned by being fired (as defined above) in an inert and/or unguided state. This applies to certain larger air-to-air missiles whose launchers are bolted to the aircraft instead of being mounted on a release unit, and to active countermeasure systems' payloads. In these cases, the jettison envelope must coincide with the operational firing envelope.

3. AERODYNAMICS OVERVIEW

The following description is now given in order to provide a very general oversight of the helicopter/store aerodynamic environment.

3.1 Helicopter/Store Aerodynamics

The aerodynamics associated with the separation of a store from a helicopter is highly complex, due to the transient nature of the surrounding environment and of the separation process itself. The environment comprises not only the flow around the fuselage due to its forward motion but also a rotor induced flowfield, the magnitude of whose velocity fluctuates in space and time.

The store's trajectory is subject to significant effects stemming from disturbances in the flowfield created by the rotor wake, the fuselage, the stores suspension system and adjacent stores. As noted already, certain military helicopter firing operations are conducted in nap-of-the-earth flight conditions, at very low airspeeds, taking advantage of terrain features to maximise the target kill ratio. This is particularly the case for attack helicopters and their more sophisticated armed utility counterparts engaged against armoured targets, and also occurs among those operators who take literally the analogy of a helicopter launching of unguided rockets as being equivalent to artillery bombardment. The store is thus subjected to significant rotor-induced disturbances (Figure 6) that may include ground effect during the first few metres of its separation trajectory.

Many helicopters, particularly the lighter ones, are equipped with undercarriage skids. Ensuring that the separation store will not collide with any part of the fuselage, including the skids, may require the store to be located further outboard than might otherwise have been strictly necessary. One result is that the store will undergo greater exposure to rotor wake effects during the first, more susceptible, moments following its first motion away from the aircraft.

Empty rocket launchers or fuel tanks, and other stores whose weights and moments of inertia are small in comparison to the aerodynamic loads acting upon them, are strongly susceptible to disturbances in the airflow and are often unstable when jettisoned. Instability and low weight often combine to create large displacement and body angle departures from the trajectory that the store would follow in a clean airflow even if the aerodynamic disturbance of the airflow is relatively small. Instability usually leads to tumbling, a phenomemum that cannot be predicted with any accuracy.

Every helicopter has an air speed envelope that contains safe and critical areas for release or jettison of its stores. A typical one is shown in Figure 7. The location of the boundary between safe and critical areas depends on the store's mass properties, ejection forces (if any), and aerodynamic loading acting upon the store.

3.2 Helicopter Flowfield Environment

The flowfield environment around the store is subject to effects created by the helicopter fuselage and its attachments, and by the main rotor. The fuselage effects are in relative terms not too difficult to model, unless the fuselage possesses protuberances such as sponsons, fixed undercarriage, or sensor turrets. These effects are highly dependent on airspeed. Rotor effects are highly complex to model and for this reason tend to attract more attention, even though they may be irrelevant to the intended separation envelopes for many stores. When planning resources for a given modelling task, the nature of the store and its intended usage are key factors.

The characteristics of the rotor wake vary considerably with the helicopter's airspeed. In the hover, the rotor wake consists of two separate parts: strong rolled-up tip vortices, and inboard vortex sheets. The vortex sheets contract and move down rapidly below the rotor plane. The tip vortices contract, roll up and move down less rapidly than the vortex sheets (Figure 8). The geometry of the wake may vary with time, due to interaction between vortices, flow fluctuations, fuselage effects and helicopter manoeuvres.

In hover and very slow forward flight conditions, the greatest component of the rotor induced velocity is the downward component while the lateral and longitudinal components are relatively small. Under these conditions, an externally mounted store's angle of attack may reach 90 degrees with a large sideslip angle (Figure 9a). The ground effect at a height of one rotor radius may reduce the total and vertical velocities by as much as 50% of the equivalent out-of-ground effect values.

The point at which the store's trajectory crosses the rotor wake boundary is of great significance. It determines the time over which the store is subjected to the region of

highest induced velocities inside the wake, as well as the position at which the store, as it nears and crosses the wake boundary, receives supplementary loads and moments due to the high induced velocities, which are highest in hover and low speed flight. These velocities also feature impulses, due to the passage of rotor tip vortices whose frequency varies with tip passing frequency, and reduces with increasing airspeed and distance in from the rotor wake boundary. Store reaction to these impulsive variations may be taken as being negligible at high airspeeds and once outside the rotor wake.

Also in hover and low speed flight, the rotor-induced downward velocity on the store increases as the store moves towards the wake boundary. This velocity decreases abruptly and then rapidly disappears as soon as the store has crossed the rotor wake boundary. The resulting pitch up effect on the store can be large, and can make a significant alteration to its subsequent trajectory. Unguided rockets are the stores that are most susceptible to this pitch up effect, especially as they are so often fired from the hover. This explains the efforts made by their manufacturers to provide rockets with very high initial velocity and spin rate profiles (Figure 10).

The rotor wake skews to the rear as forward airspeeds increase (Figure 11) until, at forward airspeeds greater than about 30 knots the rotor wake no longer impinges on the positions in which external stores are typically installed on helicopters (Figure 9b). As a result, the rotor induced effects become negligible compared with those of the free airstream. The angle at which rotor wake is skewed is primarily a function of flight airspeed and rotor disc loading.

The characteristics of the flowfield effects created by the fuselage are markedly different to those stemming from the rotor. The geometry of fuselage effects is virtually independent of airspeed: wake boundaries are almost static in space. However the magnitude of fuselage effects depends on a square law relation with airspeed. At higher velocities, fuselage effects can outweigh rotor effects by 10:1, due to the square law dependency.

4. STORE SEPARATION REQUIREMENTS

Many nations that have not created their own national standards for aircraft armament implementations adopt those of the United States. MIL-STD-1289C stipulated store separation criteria that are widely used, and steered an admirably simplistic course between the twin sins of being overly prescriptive on the one hand, or on the other hand being excessively vague. This cannot be said for some other military standards that address this topic; most merely state the obvious, in that the store must not strike the aircraft, and are of little direct guidance to the designers and developers of aircraft armament installations. Unfortunately MIL-STD-1289C has been withdrawn, apparently without a direct replacement.

MIL-STD-1289C stipulated minimum separation distances and also separation angles are also identified. While identifying satisfactory store separation distances and angles from the fuselage and from undercarriage assemblies (whether raised or lowered - if so capable), MIL-STD-1289C recognised the difficulties of predicting extreme rotor movements and advocated practical trials to confirm the safety of separation.

5. REPRISE

Up to this point, the types of store to be released have been reviewed. The various kinds of separation, as they occur under operational conditions, have also been described. Thirdly, a top level glance at helicopter/store aerodynamics has sought to outline some of the more important effects that helicopter-induced airflows may have on the store separation process. Finally, we have taken a brief look at the formal requirements regarding store separation that are (or are not) imposed by military standards. It is now time to move onto the methods that are used to predict and to measure what actually happens.

6. PREDICTIVE TECHNIQUES

6.1 Summary of Techniques

It is possible to predict a store's behaviour by analogy, if sufficient past experience exists of the separation characteristics of another store whose aerodynamic and mass properties bear sufficient resemblance to those of the store of interest.

Empirical methods make use of wind tunnel techniques, whose various approaches can provide more credible data on the aerodynamic environment around the helicopter and the store, and on the aerodynamic loadings induced by that environment. A wind tunnel survey of points throughout the flowfield adjacent to the helicopter and the initial anticipated trajectory of the store, combined with the aerodynamic characteristics of the store, can be combined to generate separation characteristics via a trajectory prediction programme.

As part of installing and integrating a weapon system on a helicopter, aerodynamic analyses are performed to establish the aerodynamic coefficients of the store and of the overall installation, and to predict the store's initial separation trajectory. There are three basic approaches to this: theoretical, analogy and empirical. Each method offers advantages and disadvantages.

Store separation theoretical predictions use fluid equations that can be coupled or uncoupled to solve the equations of motion. Coupling the fluid equations to the equations of motion allows the store's new attitude to be solved after the passage of a particular time interval. A complete store trajectory results from iterative repetitions of this process.

6.2 Analytical Methods

6.2.1 Theoretical Predictive Methods

Theoretical prediction of store separation behaviour requires reliable knowledge in two key areas: accurate representation of the flowfield induced by the rotor in the intended operating conditions, and the store's aerodynamic coefficients.

Modelling of the flowfield has shown significant progress recently with the advent of more powerful predictive techniques and computing technology, as shown when comparing Figures 9a and 9b with earlier work illustrated in Figures 12a and 12b. The rotor wake boundary is now clearly visible, as are the lower velocities within it. The effects of recirculation that are inevitable during low level or nap-of-the-earth flight regimes, and that can have a perceptible effect on the trajectories of unguided projectiles, are also noticeable. Store aerodynamic coefficients may be established theoretically with some accuracy, using developments of fixed wing work based on panel methods. The flowfield is calculated, then the aerodynamic loads on the store, from which the separation trajectory is calculated. Comparisons between theoretical analyses of this kind against wind tunnel data have shown a degree of similitude sufficient for the purposes of initial store loading and separation analyses, provided that backup analysis by other methods is also available.

Even if theoretical analysis is found to be wanting, the availability of powerful computation facilities allows a multitude of repeated runs to be performed in a comparatively short time, using Monte Carlo techniques. On this basis, while prediction of the store's separation behaviour may not be achievable directly, at least the likely boundaries of its deviation from the nominal trajectory may be predicted on a statistical basis.

An alternative approach is to combine the store's aerodynamic coefficients, if known, with a store separation trajectory programme. There are strong drawbacks to this. Helicopter stores, with a few honorable exceptions, are seldom designed and researched specifically for use on helicopters: historically, their principal markets are elsewhere, installed on either fixed wing aircraft, surface vehicles or ships. Stores from a fixed wing background tend to be backed by comprehensive aerodynamic coefficient data, but only at high airspeeds and for incidence angles within a small range around the store's longitudinal axis. This is not adequate for helicopter store separation work, for which large incidence angles can occur immediately after release during hover or low speed releases. Stores that were initially designed for launching from surface vehicles and ships should be rather better off in that at least their initial flight characteristics at low airspeeds are known, and data tends to be available for a larger range of incidence angles. Even this data is only applicable indirectly, to helicopters at launch airspeeds above 30 or 40 knots for which the effects of rotor downwash may be discounted. Sometimes store aerodynamic data is available from both fixed wing and surface launched analyses, but the benefits of combining these disparate environmental conditions to create a set of helicopter-launched characteristics are rather dubious.

The interference effects between the store, the store suspension system and the fuselage are virtually intractable, especially if the store is installed close to the fuselage to minimise aircraft centre of gravity movement during release.

Theoretical store separation predictive techniques derived directly for helicopter usage may be used at airspeeds below 30 knots with fair confidence, but not to the levels of confidence that are associated with equivalent fixed wing aircraft applications, which are backed by a considerably greater fund of experience.

6.2.2 Analogy Predictive Methods

Another approach to predicting store separation trajectories is to proceed by analogy with previous work using test data for similarly shaped stores. The analogy is only valid if comparison of many characteristics of the previous store and the store of interest show a good match and correspondingly low risk. Such characteristics include mass, moments of inertia, centre of gravity, overall geometry and installation location on the helicopter.

Freestream aerodynamic data are compared between the two stores, with any lack of experimental data being made up for by semi-empirical estimates.

Semi-empirical aerodynamic estimation codes may be combined with wind tunnel techniques such as flow angularity and grid data to provide inputs to six degree of freedom trajectory programs, at least for first order estimates of release behaviour.

Flowfield analogy's weakest link is its inability to represent interference flow field effects with any accuracy. Primary effects of this nature depend on the store's location on the fuselage, the store suspension system's aerodynamic characteristics, fuselage shape, (both locally and overall) and rotor characteristics. This flowfield is subject to disturbances arising from variations in helicopter all up weight, height above the ground or sea, and helicopter flight manoeuvres. Differences in the magnitude and line of action relative to the store's centre of gravity of any ejection force(s) is a prime consideration.

Achieving a good analogy between similar stores on a given helicopter type is entirely possible. This is fortunate, given the prevalence of store upgrade programmes as opposed to the development of brand new stores, and the top-level similarities between, (for example) many lightweight torpedoes. When the stores are noticeably

different, and especially when two different helicopter types are involved, the analogy is usually too tenuous to be of any real use.

Analogy methods do have their uses, by allowing a suitably cautious flight clearance to be granted without the cost or lead time implicit in wind tunnel testing and/or theoretical analyses.

6.3 Wind Tunnel Testing

6.3.1 Empirical Predictive Methods

After theoretical and analogical techniques, wind tunnel testing is the third approach to determining store aerodynamic coefficients and to predict separation characteristics, using a complete or partial scale model of the helicopter and an entire scale model of the store.

Helicopter wind tunnel models may include representations of the main and tail rotors; they are complex to model precisely, and are only of use for store separation testing if the launch airspeeds are below about 30 knots. At higher airspeeds the rotor wake passes over and behind the store, as already noted and therefore rotors are unnecessary.

Wind tunnel testing of store separation gives results that can be treated with high confidence, at medium to high airspeeds.

There are four basic wind tunnel techniques that are suitable for store separation testing; captive trajectory system, grid, flow angularity and free drop. Of these, free drop testing produces the best results, with good accuracy.

a) Captive Trajectory

Taking each in turn, the captive trajectory system involves supporting the helicopter and the store models on their own separate stings, such as to allow the store model freedom of (preferably remotely commanded) adjustment in all six degrees of freedom. Aerodynamic forces and moments on the store are measured using internal strain gauge balances, to generate force and moment components that are fed into a computer program together with store fixed parameter data such as mass, centre of gravity and ejection force. The equations of motion are solved for a given time increment, and the store adjusted to its new position. The process is then repeated until a complete trajectory has been completed.

b) Grid

The grid technique is a form of flowfield mapping technique. The store model is positioned in preselected positions and attitudes relative to the helicopter model. Total aerodynamic coefficient data is measured at each position, and a matrix is built up throughout the flowfield zone within which the store's trajectories are expected to lie. Subtracting the store's freestream aerodynamic coefficients from the total aerodynamic coefficients allows a matrix of interference aerodynamic coefficients to be calculated for use in subsequent trajectory calculations. This technique should be confined to small helicopter incidence and sideslip angles.

c) Flow Angularity

Flow angularity is also used to determine interference aerodynamic coefficients. Aerodynamic data is obtained using a velocity probe attached to a sting instead of the store balance combination. Velocity components are measured in a grid that encompasses the expected trajectories of the store. The store's local angles of attack are determined and the freestream lift curve slope used to generate the interference coefficients.

d) Free Drop Wind Tunnel Testing

The free drop wind tunnel techniques employ scale models of the helicopter and of the store constructed to obey specified similarity laws. The store models are released from the helicopter model in the wind tunnel.

The technique is the most commonly used and accepted method to predict separation trajectories for stores gravity-released from helicopters, although some successful work has also been carried out that simulated store ejection. (Figure 13)

High speed photography under stroboscopic lighting and video cameras record the store's trajectory. Multi-exposure photographs are taken to illustrate variations of position and attitude with time. The films are analysed to extract position:time and attitude:time data to scope the limits of a flight envelope clearance.

Static aerodynamic forces and moments are properly scaled when the model geometry and flowfield are matched to full scale flight conditions. The accelerations of the model will be similar to its full scale counterpart if the overall forces and moments, mass, centre of gravity, moments of inertia and buoyancy are also properly scaled. The Froude scaling law is the most commonly used for helicopter store separation prediction work. The proper scaling of time is the usual casualty, but is compensated for more easily than other parameters.

Free drop testing is particularly suitable when ripples or salvoes of stores have to be tested, and if the store is known or suspected to be unstable.

Aerodynamic stability at launch can be an issue with drop-launched missiles. Their aerodynamic characteristics are naturally designed to be optimised for economical cruise flight and for high manoeuvrability during the final homing phase, when the (usually) solid propellant at or near the aft end of the missile will have been expended. At launch, with

a centre of gravity to the rear of the position for optimally balanced flight, the missile may be marginally stable.

Most wind tunnels' freestream is horizontal. This leads to a systematic error when testing climbing or descent flight conditions, because the gravity component cannot be oriented correctly. Descent is usually the critical, authoritative case, in which instance the store model passes closer to the helicopter model's rear structure than should be the case in reality. This error is thus in the right direction from the safety aspect. Several store separation test programmes have shown that free drop testing tends to exaggerate rather than downplay any store misbehaviour compared to what is found during flight testing. This is also straying on the safe side.

Analytical modelling does not include the flow effects along stores and fuselages that occur in wind tunnel testing and in flight trials. These flow effects effectively reduce actual store drag coefficients, adding a further safety factor when transferring analytical results to the test environment.

7. FLIGHT TESTING

7.1 General

Store separation flight tests are the ultimate proof of the validity of preceding store trajectory analyses, that will have used whichever techniques might have been appropriate and accessible. The aircraft flight envelope authorised for initial separation tests on the basis of these predictive analyses will inevitably be very conservative. Flight testing allows envelope expansion from a starting point that is considered to be safe.

The objectives of store separation flight tests depend to some extent on whether the overall programme is for research - in which case the flight envelope may be explored in more detail and perhaps more extensively - or as part of a system installation and integration programme. In the latter case, the goal is to ensure that the system operates correctly under specified conditions, and usually does not extend to exploring the full limits of the envelope.

7.1.1 Ground Trials

It is often beneficial to conduct ground firings of relevant stores before flight testing starts.

The main reason for doing so is to provide an intermediate step in the transition from analysis to real-flight trials, partly to reduce risk by measuring initial data that will lead to a more informed judgement on how (or even if) to scope flight trials.

The other consideration is that some store separations are very hard to model accurately on a theoretical basis, either because of interaction between numerous installation fittings or because the store is new, of an unusual geometrical configuration, and/or may behave in an unexpected manner. Any decision to conduct ground firing trials must take into account the sometimes unpredictable effects of backblast effects from the ground onto the fuselage.

An example of each of these cases: firstly, a soft-mounted machine gun pintle installation, for which the vertical throw of the weapon in its installed mount is unknown, and the dispersion of the weapon itself is uncertain. Add in the behaviour of the main rotor disc, whose extreme downwards excursions in reasonably normal operational flight conditions can be large, and the case for ground firings into butts is almost unanswerable. Techniques have not greatly altered to absorb the most recent technology, because a simple target board at a known position relative to the weapon is amply sufficient to measure the actual overall throw and dispersion.

A second example of ground firings proving a useful prelude to flight separation trials is when a new missile is involved, especially if it has an unusual geometry. The techniques used are similar (on a smaller scale) to those for a flight separation trial.

A further reason for conducting ground release trials is that the store may have release features whose functions are difficult or impossible to model accurately. A ground release trials rig will be used if at all possible, but sometimes it is only feasible to achieve the necessary degree of realism by using the actual aircraft. In such cases, it may be suspended from a crane and the store released into a padded container. Whether using a rig or the aircraft, this manner of testing is usually employed for tasks of the ilk of verification of correct functioning of pull-off equipment: arming lanyards, snatch connector lanyards, folding wing retention toggles, etc.

7.1.2 Flight Trials

Whether or not the interim step of ground trials has been carried out, the purposes of in-flight separation trials remain the same, depending on the purpose of the overall programme, they may include some or all of the following:

- to provide store trajectory data to verify the results of pre-flight analysis, to complement analysis whose predictive methods may have been inexact, and to document the results of store separation;
- to acquire basic flowfield data around the helicopter;
- to determine the effects of airflow, particularly rotor downwash, on the weapon installation;
- to assess helicopter behaviour during and immediately following store separation;

- to establish the safe flight envelope for store release / firing / jettison (Figure 14).

The actual airflow around helicopter's weapon installation, and hence the effect on the store's trajectory, can only be determined throughout the aircraft's speed range by flight trials. Wind tunnel measurements provide reasonable simulations at high forward speeds, when the effects of rotor downwash are more or less absent. While engine intake suction and exhaust effects on store separation can be simulated to a degree in a wind tunnel, they are seldom relevant. On the other hand the effects on the engines of weapon firing, actually efflux ingestion, are very significant and well worth analysing - but that is outside the scope of this paper.

Captive carriage forces and moments acting on the weapon installation are measured using conventional strain gauge techniques for different helicopter-weapon configurations and flight conditions. Cross-correlation with preceding analyses, particularly wind tunnel measurements, are used interactively to improve predictive techniques, and to identify the degree of confidence with which the envelope for the next phase of flight testing may be established.

Flight separation trials (Figure 15) can commence once satisfactory captive flight trial measurements have been made. The parameters that define successful separation depend on the store in question, and might be any of:

- safe separation from the aircraft, whether passage clear of the fuselage alone for releases or jettison, or of the rotor as well in the case of firing (Figure 16);
- correct snatch connector pull-off, arming and/or wing unfolding actions (Figure 17);
- satisfactory attitude at a certain time after release, such as in the case of drop-launched ASuW missile whose boost motor must be ignited within a given pitch attitude band, or a missile whose seeker may loose lock on its target if excessive yaw occurs (Figure 18);
- satisfactory attitude rates, for similar reasons.

7.2 Flight Test Measurements

Flight test data to be obtained include:

7.2.1 Captive Store Aerodynamic Coefficients

These are measured using a five to six component force balance for various helicopter configurations and flight conditions.

a) Store Airload Parameters:

- normal, side and axial forces,
- pitch, yaw and roll moments, and
- attack and sideslip angles.

b) Helicopter Flight Condition Parameters:

- altitude,
- airspeed,
- helicopter weight,
- helicopter attitude angles and rates,
- helicopter velocities and accelerations,
- outside air temperature.
- atmospheric conditions and wind direction/speed, and

In ground effect:

- wheels/skids height above ground.

In order to measure store loads, a five to six component force and moment balance, built into a shape representing the store, and a magnetic tape recorder onboard the helicopter are necessary to record the loads and flight conditions. Also, strain gauges are employed to measure stress directly or to measure axial loads or bending moments on the store or its suspension system. These parameters are measured for various flight conditions, as appropriate to the type of store, such as:

- hover in ground effect,
- hover out of ground effect,
- horizontal flight at different altitudes,
- climb and descent,
- autorotation,
- sideslip flight,
- manoeuvring flight.

7.2.2 Store Separation Parameters

The following parameters should be measured, in addition to the helicopter flight condition parameters already mentioned.

a) **Store Mass Properties (for each individual store, if feasible)**

- weight,
- centre of gravity,
- moments of inertia.

b) **Store Drop Conditions:**

- store carriage position,
- store attitude angles and rates (pitch, yaw and roll),
- store accelerations,
- time of release.

c) **Store Separation Trajectory Data:**

- store attitude angles and angular rates,
- store linear and angular displacements.

7.3 Flight Test Instrumentation

As in any testing activity, parameter measurement should never influence the behaviour of the test 'specimen'. Instrumentation on the store and on the aircraft must not induce aerodynamic or dynamic behaviour outside the norm of the uninstrumented installation.

Flight test instrumentation for measuring store separation data should include:

- a central time code, by which all parameters may be time-correlated regardless of their measurement source. When recording the release of individual stores on film or video, a 'fire' indicator light mounted on the aircraft fuselage and illuminated simultaneously with the firing pulse is superior to relying on visual detection of the store's first motion;
- normal and high-speed film and video cameras, mounted on the launch aircraft. Depending on the nature of the store, these cameras may record the separation characteristics of the store, the behaviour of arming and other lanyards, and the proximity of the store to the fuselage or the main rotor;
- a chase helicopter to provide a more general perspective of the store separation and to record data on camera from angles that would not be available to the launch aircraft;
- ground-based theodolite cameras, to provide more accurate parameter measurement than can be achieved by cameras in chase aircraft;

In certain situations ground-based radar can provide useful data, although it is better suited to measuring store behaviour farther down the trajectory.

Conventional film and video cameras are the norm, but infra red cameras do have their uses in particular circumstances. Infra red cameras have previously been used to record thermal effects on the helicopter (fuselage heating, engine intake ingestion), but can also provide a clearer contrast between the helicopter and/or the store and the background.

The most significant recent advance in store separation flight test instrumentation concerns the miniaturisation of telemetry packs. A few years ago it was only feasible to telemeter whole missiles, usually by substituting the telemetry pack for the store's warhead section. It is now practical to measure comprehensive data from within submunitions or subprojectiles, greatly augmenting the accuracy achievable by remotely-mounted instrumentation and sometimes rendering it redundant.

The other major advance, which applies to flight testing in general, is the ability to transmit data from the launch aircraft, the chase helicopter and the store(s) to a ground station within which it may be analysed almost in real time. This allows an anomalous flight condition to be repeated immediately, or store separation trials that are showing unexpected behaviour to be halted at once for further analysis without wasting precious hardware and time resources. The recording of data on board the launch and chase helicopters is still of great value for backup purposes or for limited trials being run within a very tight budget.

8. CONCLUSIONS

The techniques used to predict and to measure store separation trajectories from rotary wing aircraft have evolved from those used in the fixed wing domain, but have had to adapt to the lower Mach numbers, much more complex flowfields and (often) less aerodynamic stores used in the rotary wing operating environment.

The choice of prediction techniques naturally varies from organisation to organisation, depending on the availability of skills, database and facilities, but a consistent trend towards computer modelling of store behaviour is very evident even if the extent of the unknowns can force the use of statistical rather than absolute predictions. This trend would not be possible without the rapid evolution of applications and hardware that has occurred over the last decade.

In a similar vein, the rapid acquisition, transfer and analysis of wind tunnel and flight test data have been transformed by technological progress.

Store separation will never be an exact science. Despite the rate of development of predictive techniques, they will never displace flight trials. Their real contribution is to the lowering of overall programme costs by increasing confidence in the predicted flight envelope before flight trials begin, and reducing the extent of flight trials that are necessary.

A sound store separation programme will employ a balanced suite of techniques, including analytical, wind tunnel and in-flight testing.

Acknowledgement

The author wishes to thank colleagues in GKN Westland Helicopters and other organisations who have helped with the preparation of this paper.

REFERENCES:

1. AGARD Integration of Externally Carried Weapon Systems with Military Helicopters AGARD-AR-247.

2. AGARD Flight Test Techniques Series Volume 10, on Weapon Delivery Analysis and Ballistic Flight Testing. AGARD-AG-300 Vol 10.

3. MIL-STD-1289C. Airborne Stores Ground Fit and Compatibility, Requirements for. 17 January 1995.

4. DEF STAN 00-970. Design and Airworthiness Requirements for Service Aircraft. Volume 2 - Rotorcraft.

5. Cannet, M. Air-to-air Fighting with Helicopters. International Defense Review, 8/1988.

6. Ford, B.M. Attack Helicopters in the CAS Mission. Rotor Mission 2000, October 1995.

7. Fry, L.D. Adaption of Sting Ray Torpedo to Various Aircraft. Royal Aeronautical symposium, February 1995.

8. Jenkins B.Z. The Aerodynamic Environment of Rockets Launched from Helicopters. Proceedings of the Ninth Meeting of the Technical Cooperation Program Panel W-2 held in Canada. Volume 1, 1984. Eighth European Rotorcraft and Powered Lift Aircraft Forum, 1982.

9. Kukutsidis, D. and Wall, R.H. Advances in Rocket Weapon Systems for Helicopter Applications. Fighter Helicopter Conference, London. January 1994.

10. Kukutsidis, D. CRV7 C17 Rocket Spin Profile Optimization for Helicopter Applications. Rotor Mission 2000, October 1995.

11. Landgrebe, A.J. The Wake of a Hovering Helicopter Rotor and its Influence on Hover Performance. Journal of AHS Vol.17 No.2, 1972.

12. McBeath, J.R.B. Effective Delivery of Unguided Weapons from Helicopters. Royal Aeronautical Society Symposium: Helicopters as Weapon Platforms, February 1996.

13. Wills, T.G. Range Safety. Royal Aeronautical Society Symposium: Design for Safety, April 1991.

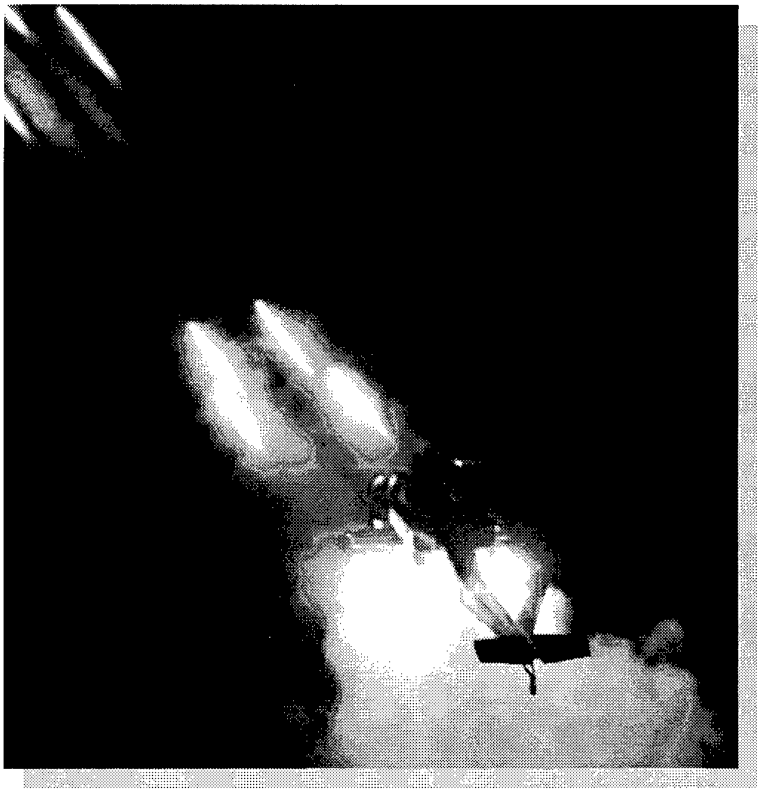
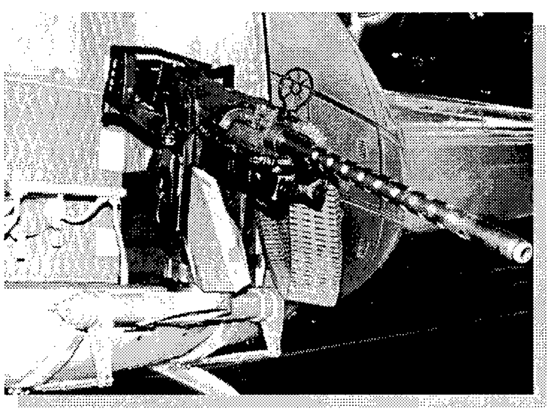
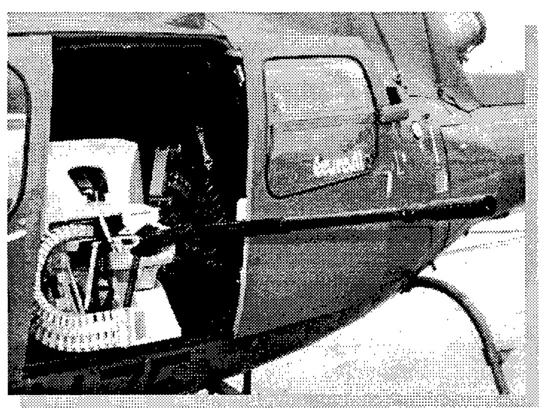


Image : McDonnell Douglas Helicopter Systems

Figure 1 - AH-64D Apache Firing CRV7 2.75 Inch Rockets During Firing Trial



FN Herstal 0.50 inch Medium Pintle
Head in Bell 212 Helicopter
(Image : FN Herstal)



GIAT Industries 20mm MS621
in Eurocopter Fennec Helicopter
(Image : Eurocopter)

Figure 2 - Pintle Mounted Gun Installations

Image : McDonnell Douglas Helicopter Systems

Figure 3 - On the Modern Battlefield, Helicopters must Operate and Fire at Low Altitudes (AH-64A Firing Hydra 70 2.75 Inch Rockets)

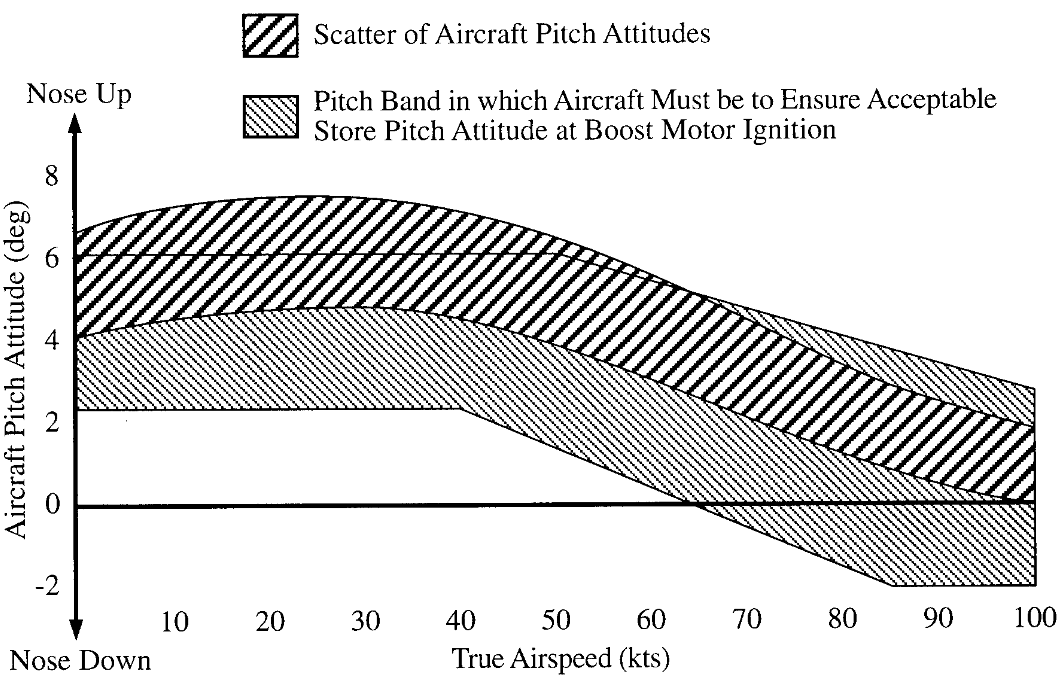


Image : GKN Westland Helicopters

Figure 4 - Example of Mismatch Between Aircraft's Natural Flight Attitude & Attitude Required for Correct Store Release

Figure 5 - Wing Tip Installation of Air-to-Air Missile Launchers (Illustrative)

Figure 6 - Lynx Helicopter Firing Hellfire Missile

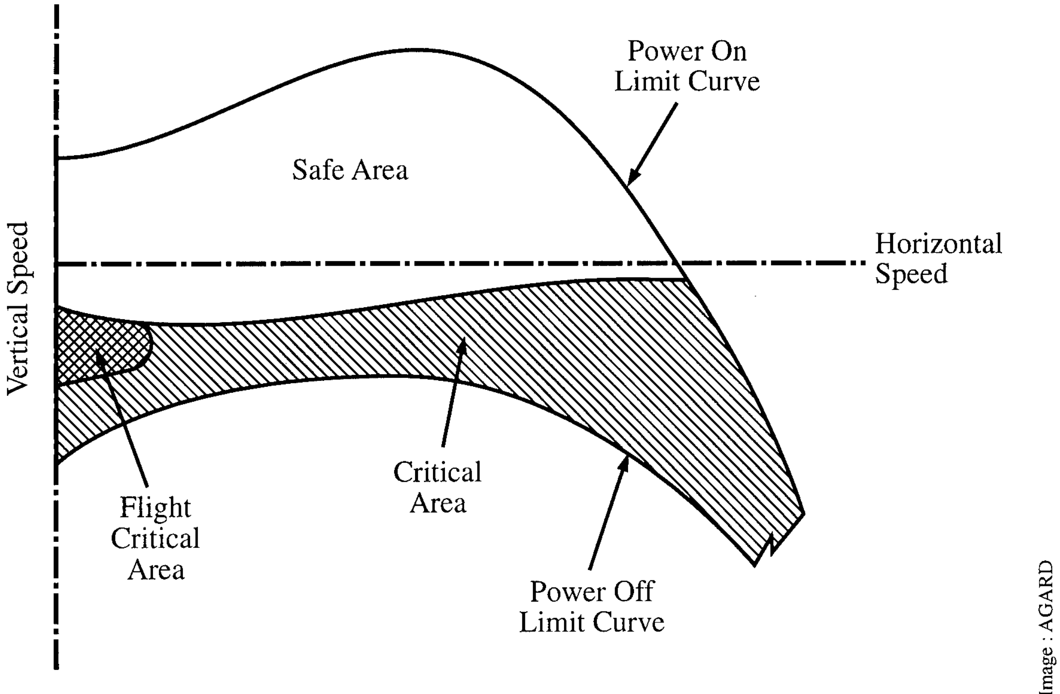


Figure 7 - Typical Helicopter Horizontal Speed Versus Vertical Speed Store Separation Flight Envelope (Power On / Power Off)

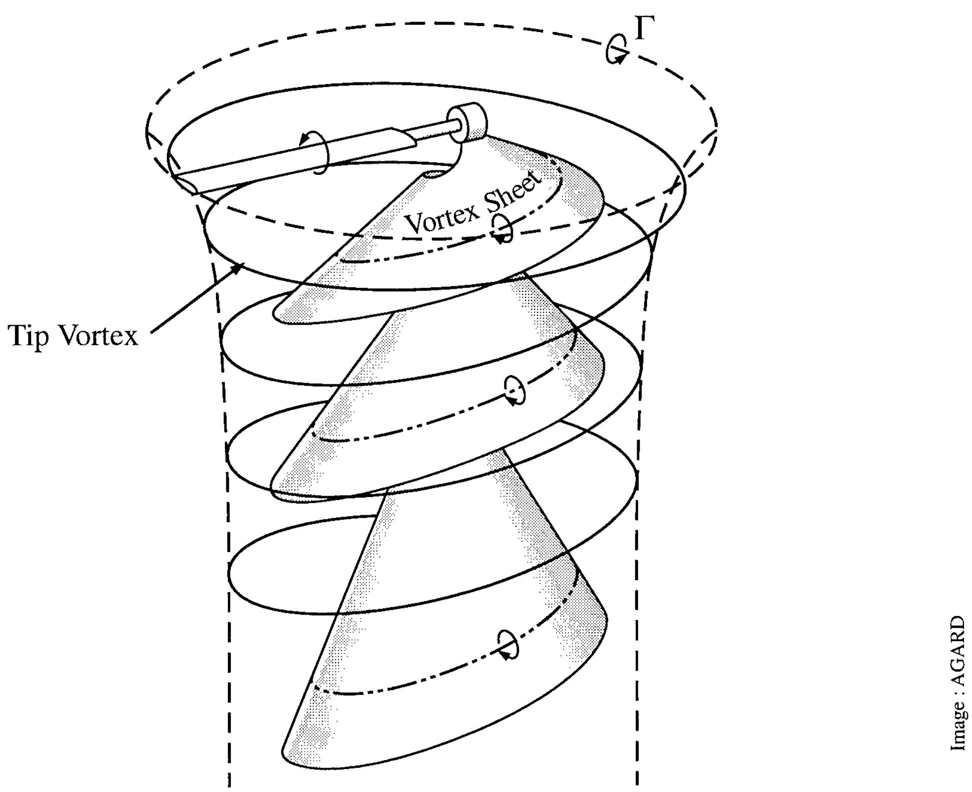


Figure 8 - Rotor Hover Prescribed Near Wake

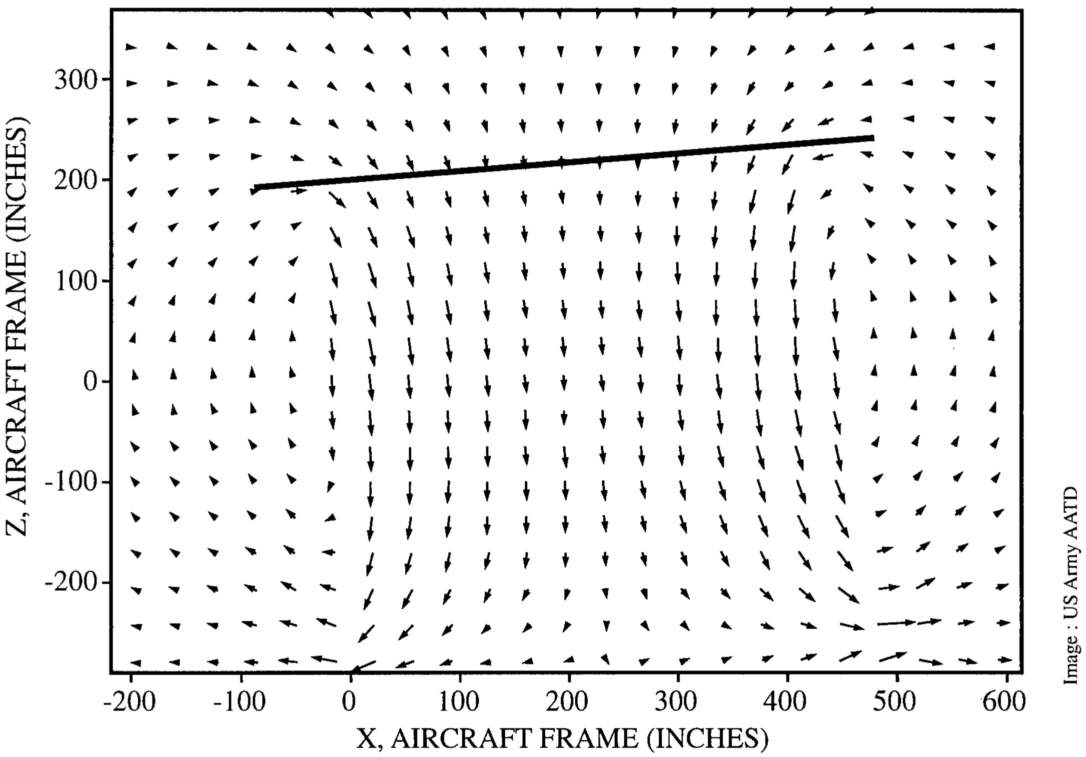


Figure 9a - Downwash Flow Field for VAC = 0 KTAS at 30 FT AGL (side view)

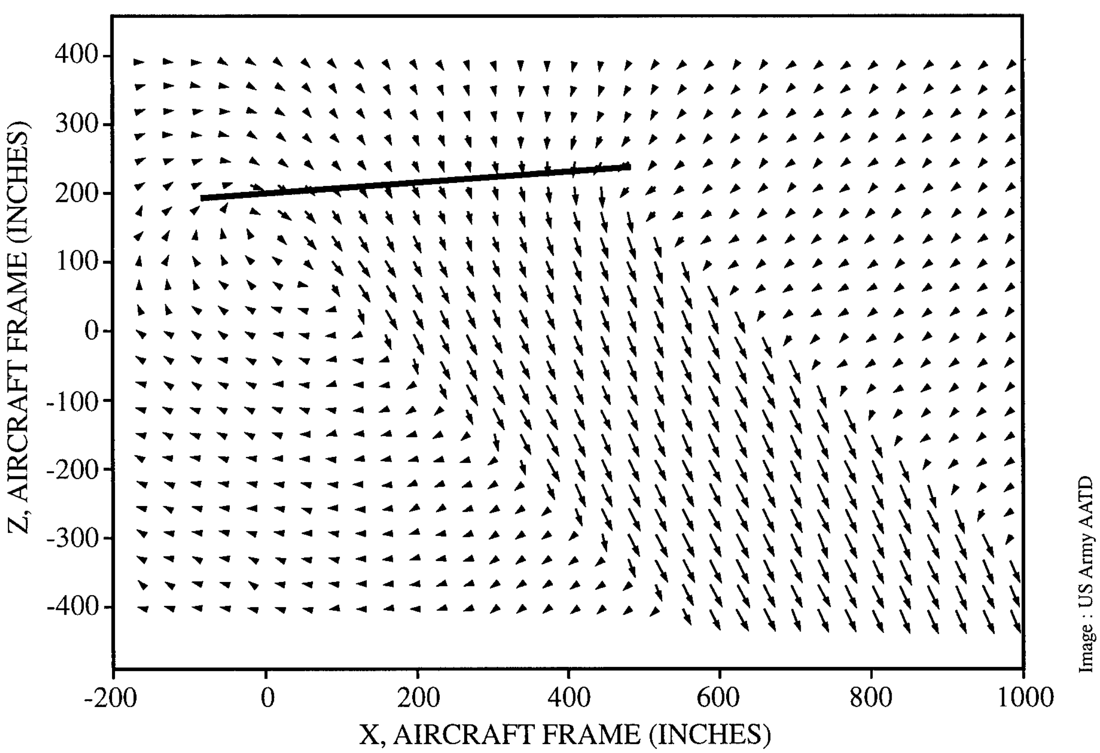


Figure 9b - Downwash Flow Field for VAC = 20 KTAS at 100 FT AGL (side view)

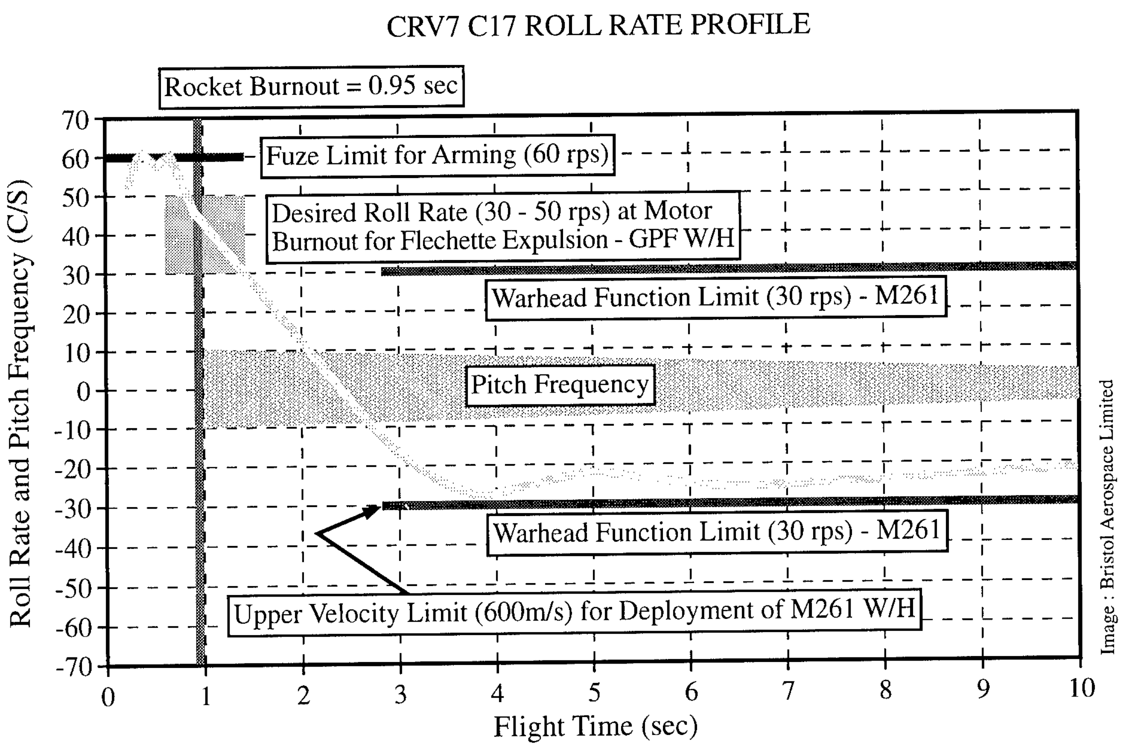


Figure 10 - CRV7 2.75 Inch Rocket Weapon System C17 Motor Characteristics

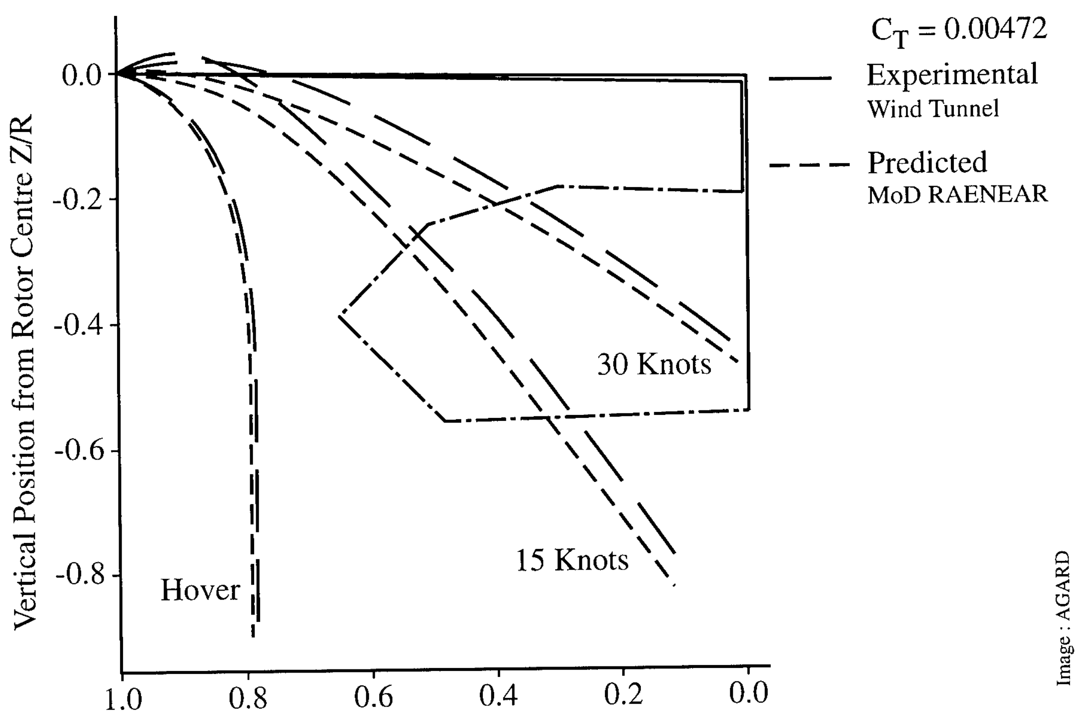


Figure 11 - Front Rotor Wake Boundary Position Variation with Forward Speed Flight. AH-1G Helicopter

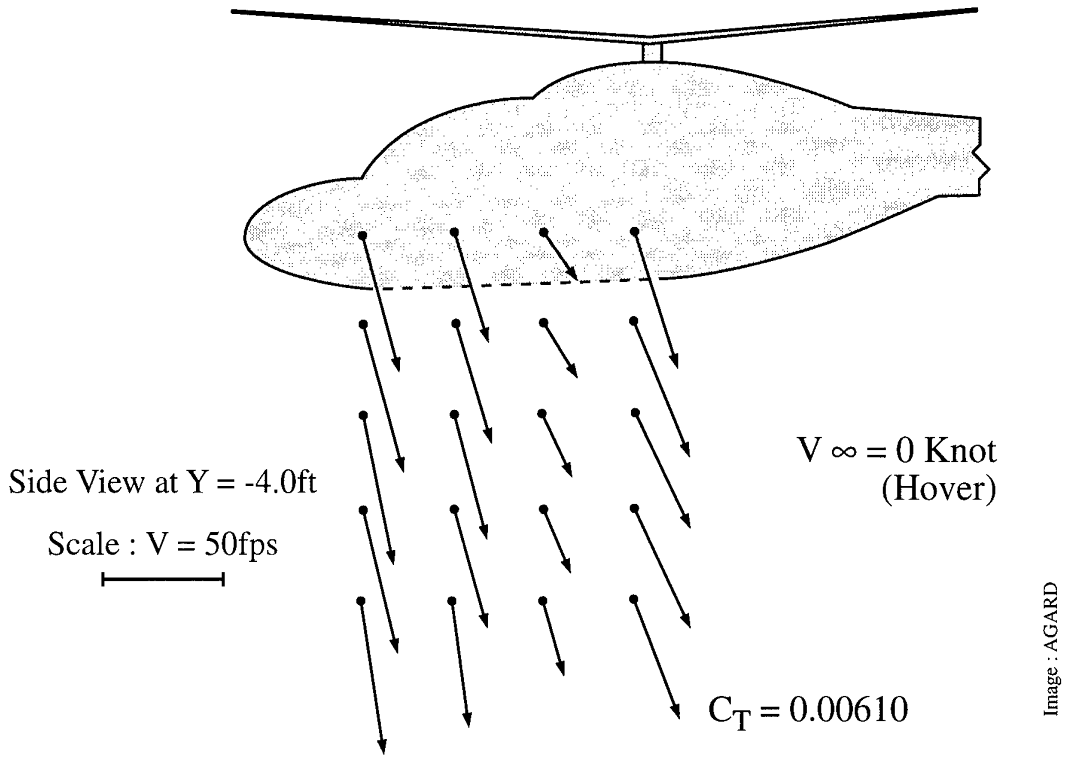


Figure 12a - Modified RAENEAR Lynx Helicopter Calculated Flowfield

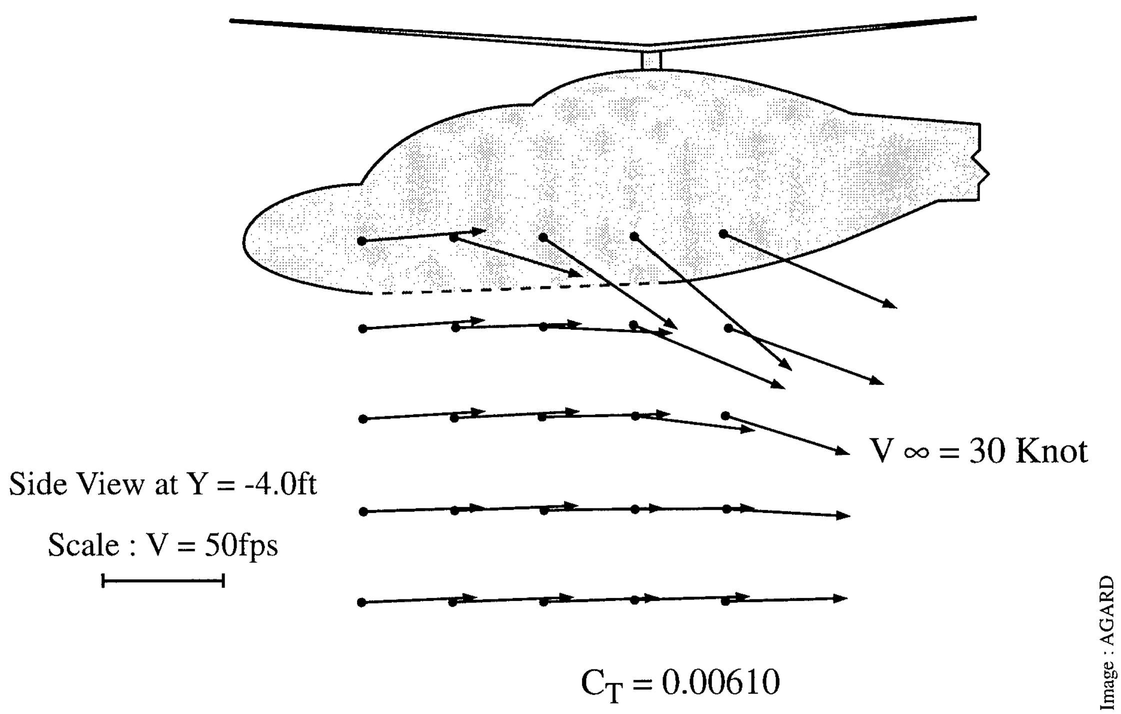
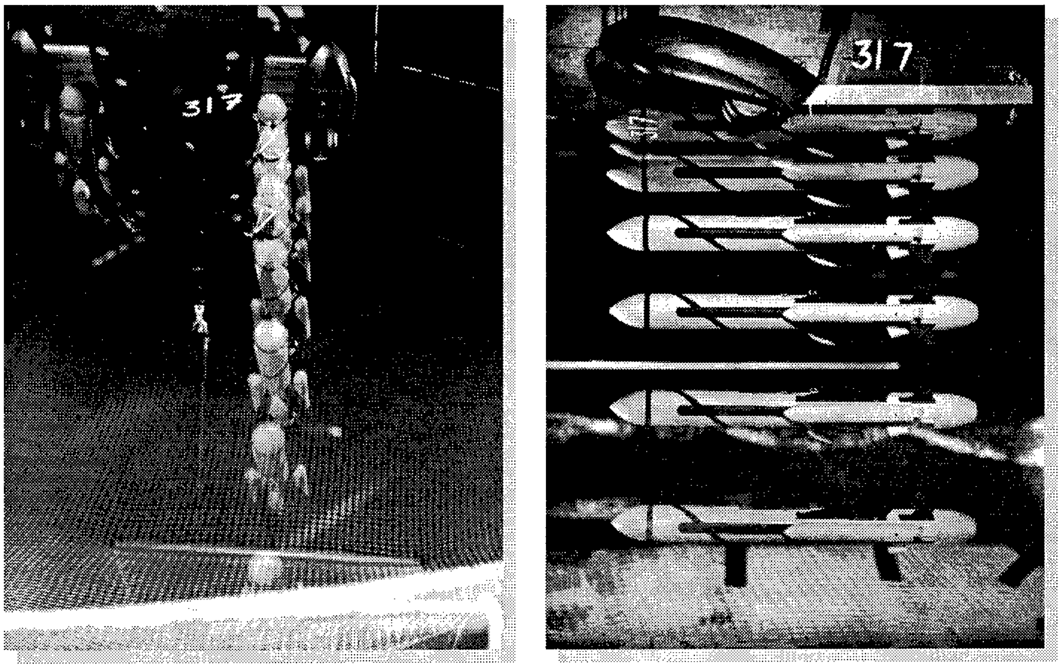


Figure 12b - Modified RAENEAR Lynx Helicopter Calculated Flowfield



Images : GKN Westland Helicopters

Figure 13 - Wind Tunnel Release Trials of Large ASuW Missile from Sea King Helicopter

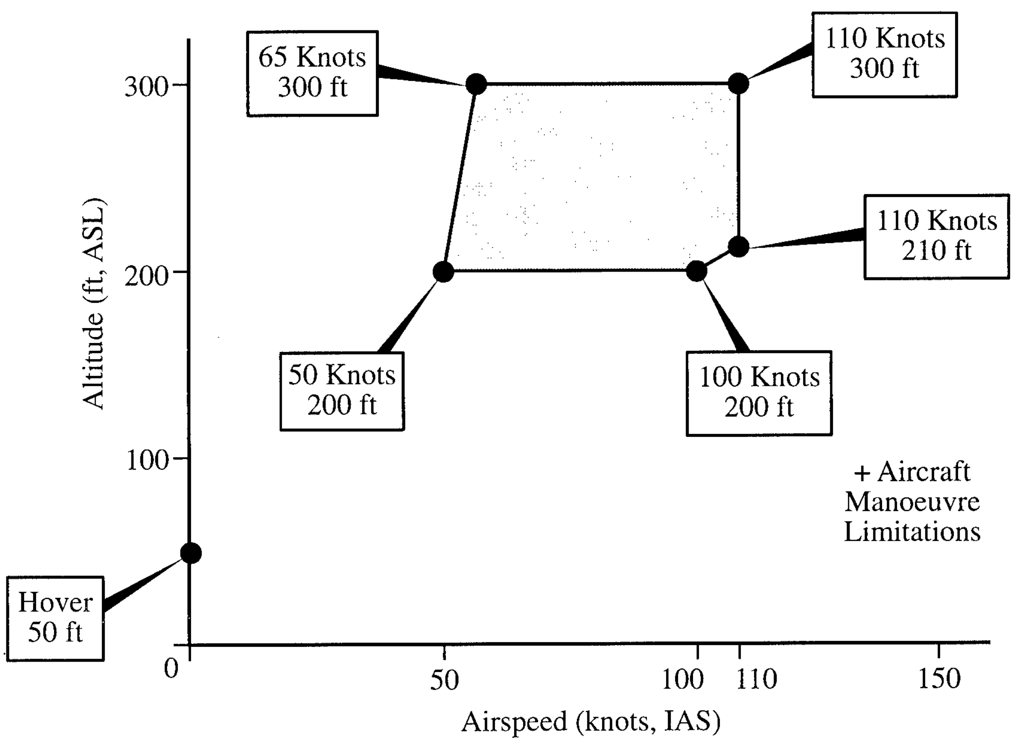


Image : GKN Westland Helicopters

Figure 14 - Typical Torpedo Release Envelope

Image : GKN Westland Helicopters

Figure 15 - Release Trials of Large ASuW Missile from Sea King Helicopter

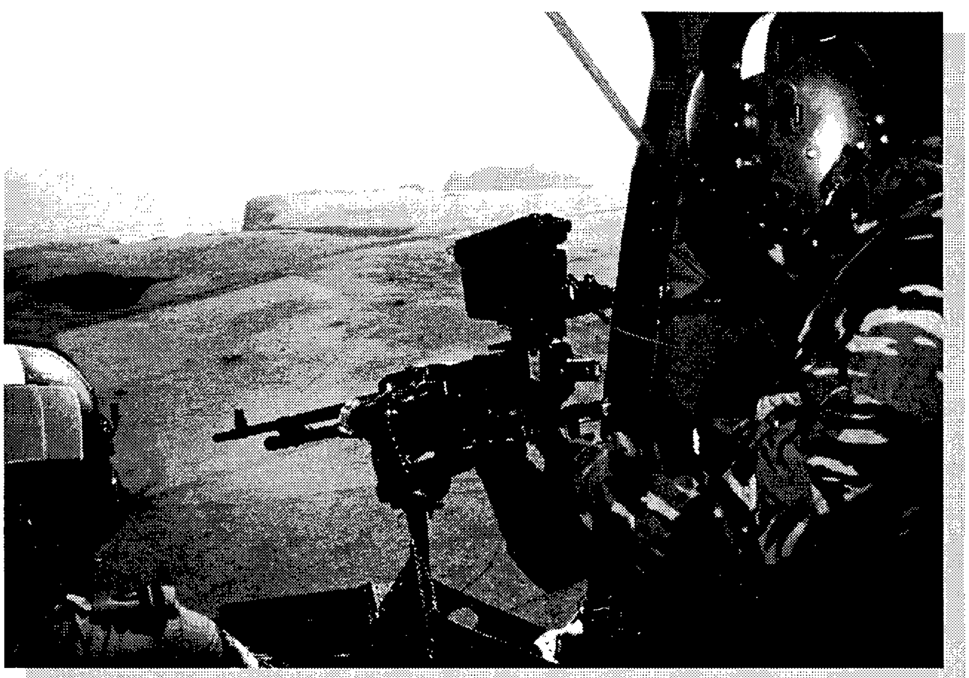
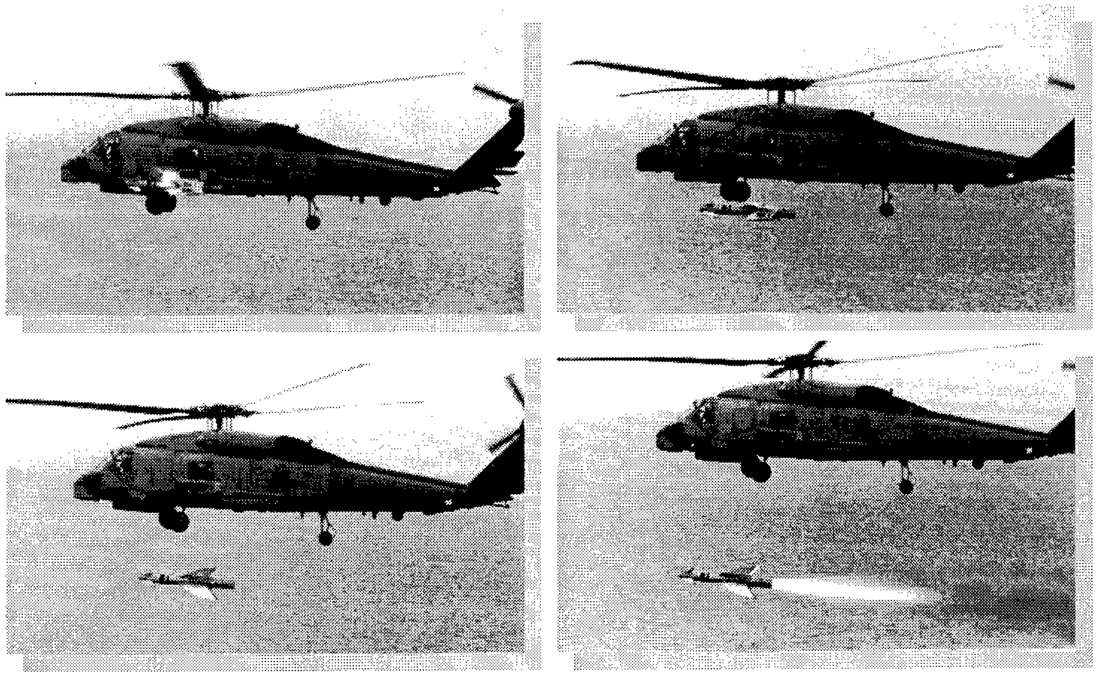


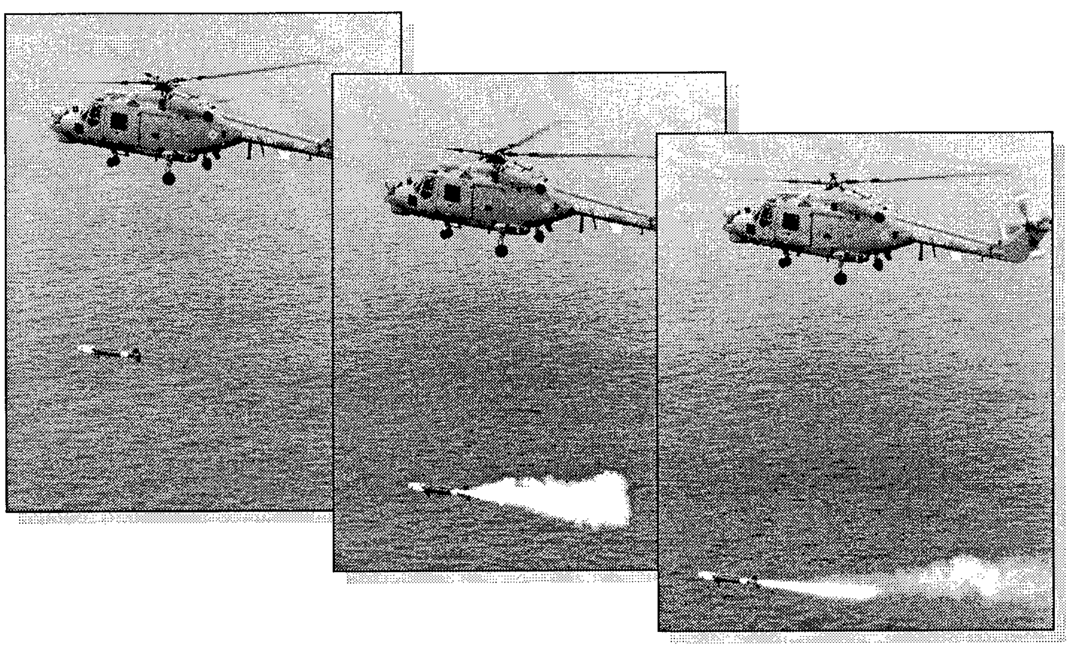
Image : Ring Sights Defence Limited

Figure 16 - Firing Trial of Pintle Mounted 7.62mm Machine Gun



Images : Kongsberg Aerospace

Figure 17 - Release Trials of Penguin ASuW Missile from Seahawk Helicopter



Images : Peter Holman, Motordrive Photographic

Figure 18 - Royal Navy Lynx HMA Mk.8 Helicopter Releasing Sea Skua ASuW Missile

Helicopter Weapon System Integration
Session 2: Structural Mechanics
Loads, Dynamics / Vibrations, Acoustics

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1. SUMMARY

Loads, dynamics/vibrations mechanics and acoustics are on one side classical disciplines which contribute to the integral helicopter layout. However in the context of weapon system integration they are the key areas where direct interfacing problems may arise between the basic helicopter and e.g. an external weapon store or a sight system.

This lecture provides a view over technology options and methodologies for the structural mechanical layout of the total helicopter. Basic tasks like the establishment of a static and fatigue flight load survey or proper frequency placement in the fixed and rotating frame are recalled as well as the necessary activities in component, ground and flight testing. Important regulations and military requirements will be discussed. Special consideration will be given to weapon component specific load and vibration example cases, like missile launching loads, gun recoil forces, blast overpressure and missile hangfire. The influence of in-flight airframe structural deformations on the harmonized line-of-sights of weapons and sight systems will be discussed.

In acoustics, after an excursion on noise sources and phenomena, informations will be given on internal noise requirements and acoustic detectabilility. The noise chapter concludes with a discussion on the noise reduction potential of different helicopter design parameters.

The lecture is supported by example material gained during according development activities of the authors company (BO105, EC135, TIGER, NH90).

2. LIST OF SYMBOLS, ABBREVIATIONS

V	flight speed
V_h	maximum level flight speed
V_{ne}	never-exceed flight speed
V_d	limit design speed
n	number of blades
Nr	rotorspeed
n_z	vertical load factor
Ω	rotorspeed, rotor rotational frequency
ω_ζ	rotor blade lead-lag natural frequency
ω_β	rotor blade flapping natural frequency
AFCS	automatic flight control system
ATAM	air-to-air missile
ATAS	air-to-air STINGER
CF	centrifugal
CG	center of gravity
EMS	emergency medical service
FAA	Federal Aviation Administration
FEM	finite element method
ICAO	International Civil Aviation Organization
LOS	line of sight
MCP	maximum continous power
MGB	main gearbox
OGE	out of ground effect
PAH	Panzerabwehrhubschrauber
PT	prototype
r.m.s	root mean square value
SAR	search and rescue

3. LOADS

3.1 Requirements Overview

Basic airworthiness requirements concerning static design loads for flight, landing and ground operations are formulated in the U.S. Federal Airworthiness Regulations (FAR) part 27 for helicopters up to 2700 kg maximum weight and part 29 for the heavier ones /3/.

Static flight load cases with detailed manoeuver descriptions are required in the MIL -S - 8698, /4/.

Design load requirements for landing and ground operations are to be found with either correspondences or mutual references in the FAR, MIL -S-8698 and ANC-2 bulletin /5/.

Design crash load requirements are defined in the MIL-S-1290 with partial references also to the AR56 of the U.S.Navy /6/, /7/.

Already this short listing of civil and military load requirements demonstrates the formal complexity for certification of helicopter structures in military programs.

3.1.1 Flight Loads

Although military forces themselves have certification authority, it is not erroneous to mention the FAR, a civil regulation. Military helicopters are often derived from civil versions or are involved in civil operations (e.g. EMS, SAR) during peace time.

Flight loads in the FAR are addressed under "Subpart C - Strength Requirements" (see fig. 3.1.1-1). The initial paragraphs of the regulation ask for a consistent design data base e.g. for weight, center-of-gravities (CG), schedules for flight and rotor speeds. For limit (static) flight loads , load cases like extreme turns or yawing manoeuvres have to be derived from the more general directives given in the related paragraphs for the vertical maximum design load factor or yawing conditions. Other limit flight load cases are "hidden" in requirements for aircraft components of the control system, rotor support structures or auxiliary lifting surfaces. Astonishing is the missing of requirements in the FAR for certain load intensive asymmetrical manoeuvres, like a rolling pull-out.

Such manoeuvres are explicitely required and described in the MIL-S-8698 chapter 3.2 "Flight and take-off loading conditions". (see fig. 3.1.1-1). Some military helicopter projects (e.g. TIGER) use therefore a combination of requirements for limit flight loads from the FAR and MIL-S-8698.

Paper presented at the AGARD FVP Lecture Series on "Helicopter/Weapon System Integration", held in Winchester, UK, 19-20 May 1997; Athens, Greece, 22-23 May 1997, and published in LS-209.

As concerns the fatigue loading a substantiation based on flight testing and a realistic operational spectrum is required in the FAR (§ 29.571).

3.1.2 Landing and Ground Loads

Described in far more detail than flight load cases are those for landing and ground operation (with wheeled landing gears) in the according military requirements.
Three important landing cases in vertical direction are noteworthy:

- Normal landing with vertical velocity 2.44 m/s and lift to weight ratio = 2/3
  No damage on helicopter parts (limit load condition, FAR29 and MIL-S-8698 both applying landing gear test drop heights of 8'' with reserve energy dropheight of 1.5 x 8'')
- Hard landing with vertical velocity 6.1 m/s (20 ft/s)
  Damage of landing gear and blades allowed, remainder of aircraft has to be flightworthy, lift to weight ratio = 1
  (ultimate load condition, MIL-STD-1290)
- Crash landing with vertical velocity 12.8 m/s (42 ft/s) with landing gear extended,
  lift to weight ratio = 1 no height reduction of cockpit or troop compartments by more than 15% or no injurious accelerative loading for the occupants.
  (ultimate load condition, MIL-STD-1290)

For detailed landing gear and fuselage design to landing and ground requirements there exists an exhaustive number of load cases. As an example a list of load cases collected from the FAR29, MIL-S-8698 and consequently from the ANC-2 bulletin for normal landing with the nose-wheel type landing gear is shown in fig. 3.1.2-1. For crash impact design conditions with landing gear extended according to MIL-STD-1290 a list is given in fig. 3.1.2-2.
Detailed design load requirements for the landing gear for ground manoeuvering, such as taxiing, braked roll, pivoting, turning and obstruction loading are to be found in the AR56 from the U.S. Navy.

3.2 Design and Verification

Prediction and establishment of design loads in a helicopter project should be based on consistent data, describing the aircraft architecture in geometry and masses, desired operational ranges, dedicated missions, power installation and performance. Component, ground and flight tests are necessary and required by regulations to verify the load assumptions of the design phase.

3.2.1 Flight Loads

Mission and architecture are determining the flight loads behaviour. This may be supported by photos of the BO105, a multi-purpose helicopter, NH90 military transport and TIGER, a combat helicopter in fig. 3.2.1-1 in combination with their mass/CG diagrams in fig. 3.2.1-2. Determined by their multi role transportation task, the BO105 and the NH90 have rather large longitudinal CG ranges (33-45 cm), resp. a large offsets of the CG from the main rotor center line. This has a strong influence on the main rotor mast bending moment. Interesting is here the forward CG in turn manoeuvres for low cycle fatigue and aft CG for endurance flight states like level flight with V_h. This is not an issue for TIGER, which mainly carries all the useful load on the stubwing in the nearer vicinity of the main rotor station. Static limit flight loads have to be calculated on the boundary of the load factor / flight speed envelope ("n_z-V-envelope") an example of which is depicted in fig. 3.2.1-3 for the TIGER project. This structural design flight envelope considers the following capabilities of the main rotor:

- high speed V_d:	Mach number of advancing blade, remaining controllability at V_{ne} in combination with stall on-set on retreating blade (V_d=1.11*V_{ne} !)
- high load factor:	Max. thrust capabilities according to the chosen airfoil technology, Max. rotor speed Nr in transient autorotation conditions
- negative speeds:	In practise the max. required wind speed from the rear
- negative load factors:	-0.5g (e.g. MIL-S 8698) , an issue for high hinge-offset main rotors

The direct "limit load" flight situations on the structural flight envelope originate from calculatory transient manoeuvres like

- symmetric dive and pull-out
- rolling pull-out from an autorotation at max. transient rotor speed
- push-over, etc.

Here the inertia reactions, resp. the angular accelerations about the aircraft axes play the supreme role in the loads generation for main rotor and fuselage. Also aircraft reactions to gusts from all directions have to be considered.
Related to flight practise these limit load flight cases can be sorted into the category of emergency cases (e.g. sudden evasive action before flying into power lines or to avoid bird strikes, etc.). Their probability of occurence is extremely remote. These loads can only be obtained by calculation or by extrapolation from special structural substantiation flight tests and have to be multiplied by a safety factor of 1.5 before being assessed as a static stressing of the aircraft structure. A result of such a static flight load prediction for the main rotor thrust and the mast bending moment of the TIGER project is shown in fig. 3.2.1-4.
The n_z-V-envelope does not take care of lateral manoeuvres like spot turns or pedal reversals in the forward flight speed range. For the project a so-called side-slip envelope has to be established and for the according yawing flight cases the limit loads have to be calculated.
The features of a simulation model in support to the static design load prediction are outlined in fig. 3.2.1-5. In summary it can be stated that a helicopter flight mechanical analysis computer code with a trim part and the ability to perform a subsequent transient simulation (control inputs, gusts) is needed. Necessary background theory on helicopter modelization for motion and loads calculation is provided in /1/, /2/.
Each helicopter applying for FAA certification has to undergo a fatigue evaluation by an inflight measurement of all loads and stresses throughout the range of design limitations for rotor speeds, flight speeds, weight and CG, except that manoeuvering load factors need not exceed the maximum values expected in operation (FAR29.571).
The methodology of this fatigue evaluation is shown in fig. 3.2.1-6. The helicopter, instrumented for a loads measurement on all interesting components of the dynamic system and the fuselage, has to perform a flight and a ground test program, which is based on the specified flight state (occurence) spectrum, also called mission profile /8/, /9/ (table bottom left in

fig. 3.2.1-6). The flight test analysis task consists of counting all load cycles occuring in all operational states of the helicopter. The occurence of the flight state and the counting result of the load in this flight state has to be folded, to give the combined probability of occurence of this load with respect to its statistical variables, the momentary mean value and amplitude. The terms 'mean value' and 'amplitude' are used in the sense of the RAINFLOW-Method, a standard for counting fatigue load cycles /36/. These are the only interesting values to calculate the cumulative damage (PALMGREN-MINER) at the aircraft component of interest on the basis of the according WÖHLER curve of the components fatigue strength (see fig. 3.2.1-6 bottom right).

3.2.2 Landing and Ground Loads

Load calculations for normal and hard landing as well as ground manoeuvering can be performed with a mathematical model which considers the 3-dimensional rigid body motions of the fuselage. It incorporates the exact landing gear kinematics and degress-of-freedom. The non-linear properties of the gas spring and oil damper unit has to be modelled. For ground manoeuvres it is necessary to consider also the surface / tyre contact and adhesion dynamics. The basic definitions of such a model are outlined in fig. 3.2.2.-1. The modelling techniques are here very similar to the vehicle dynamics applied in automotive engineering.

More complex are the models needed for crash behaviour prediction. Best known is the computer code KRASH, a former development of the Lockheed-California Company. The model consists of lumped masses and interconnecting massless beams. The mass points are used to specify the correct mass of the vehicle, the center of gravity and moments of inertia. Correspondingly the beams have to represent the structural properties of the fuselage. Further necessary are spring elements which provide the contact to the impact surfaces. A more detailed description of this code and the application to the systematic development of the crashworthiness of the NH90 helicopter is presented in /15/. An example result of a NH90 crash simulation is depicted in fig. 3.2.2-2.

3.2.3 Component, Ground and Flight Testing

Supplemental to the establishment of design loads for the helicopter project are the experimental activities for strength evaluation of component or major subsystems in laboratories, on whirl towers, ground test articles, etc..

Complete critical structural samples of the helicopter are tested on hydraulic loading benches for static and fatigue strength. For the latter the component WÖHLER curves are evaluated in tests, especially for composite rotor structures, due to the high complexity of cross sections and load paths. Standard load sequences for rotor component fatigue and crack propagation tests were established by special working groups ("HELIX, FELIX", /11/).

A combined flap / lead-lag bending, torsion test under simulated centrifugal (CF) load for the TIGER main rotor blade neck and CF retention lug is shown in fig. 3.2.3.-1.

For TIGER a complete fuselage including the empenage has undergone a fatigue and static limit load test after having artificially aged the structure in an environmental conditioning chamber. An impression of the test arrangement with the dedicated prototype PT6 is presented in fig. 3.2.3-2.

Drop tests with the TIGER landing gear were also performed in the same institution (fig. 3.2.3-3).

During the development phase there are dedicated flight tests to support to the design optimization of load critical components. For certification (see chapter 3.2.1), a fatigue evalution, based on in-flight measurements in the whole flight envelope, has to be performed. These tests contribute significantly to the cost of the certification flight test programme. In the TIGER programme, 37 flight hours were spent to perform the structural substantiation flight tests for FAR29.571 on two prototypes. The measurement data base now consists of 1000 single manoeuvre, altitude and configuration cases for 100 stress measurement parameters.

3.3 Special Considerations for Weapon Systems

3.3.1 Flight Loads and Military Operations

Military operations have an influence on the loads behaviour. This has to be considered in the integral helicopter development.

There can exist important differences between the civil and the military mission spectrum. This is insofar of interest when an existing civil helicopter type has to be adapted to military missions as was the case with the BO105. This helicopter was initially developed for civil multipurpose missions, like EMS, legal enforcement, off-shore transport, executive transport, etc..

In all these civil missions it seems to be a great emphasis put on the level flight segment of the mission profile (more than 60% relative occurence, see fig. 3.3.1-1). The hover is only represented with 5%. The military mission profile of the BO105-PAH1 in its light anti-tank role consequently shows a rather large hover portion having the same relative occurence percentage as the level flight (approx. 30%).

Certain mission task elements of combat helicopter missions represent demanding challenges for the rotor structures, engines, drive train and fuselage structure. In the "Handling Qualities Requirements for Military Rotorcraft", ADS 33C /35/, special aggressive task manoeuvres have to be demonstrated:

- quick acceleration/ deceleration
- rapid sidestep
- rapid bob-up and bob-down
- combined pull-up/push-over
- rapid slalom
- fast transient (180°) turns at an altitude of 100 ft
- roll reversals at reduced and elevated load factors

Another case where the helicopter loads behaviour and military operations may interact, is the danger of collision between the weapons delivered and the blades of the main rotor. If the clearances are not sufficient a missile or gun projectile may hit the blade when it is extremely flapping downward in the front quadrants of the rotor disc (fig. 3.3.1-2). This may happen in push-over situations during air-to-air combat. The hard stops of the elevation slaving units of guns or launchers must be adjusted such, that intercepts with the blades are avoided in all operational states.

3.3.2 Weapon Specific Load Cases

Dedicated weapon integration engineering efforts are needed for the design of attachments, interfaces between launchers, gun pods or visionic systems like roof or mast mounted sights. The operation of heavy guns (e.g. calibre 30 mm) requires an extra compensation of attitude disturbances due to the large recoil forces by the flight control system (AFCS).

Stubwings or strut constructions as carriers for launchers or rocket/gun pods have to be designed to withstand the forces from the weapon, to avoid resonances neither with helicopter excitations (n/rev, blade passing harmonic) nor with the weapon itself (gun firing cadence). Gun recoil forces may necessitate the

application of shock absorbers to protect sensible equipment of the helicopter (cockpit instrument panels, navigation equipment, etc.). Special stiffness requirements for the weapon carrying and sight system structures have to be considered to minimize the in-flight deflections of the line-of-sights of weapon and visionics and to provide the required precision for lock-on and hit probability.
An impression of the forces exerted from weapons onto its carrying structure can be gained by the figure 3.3.2-1. Here a measurement is shown from flight/ firing tests with the HMP/MRL 70 combined machine gun (0.5'') / modular rocket launcher (4 rockets) on a BO105 (see fig. 3.3.2-2). The time histories show the lead-lag bending moment and the torsional moment of the horizontal weapon carrier tube during a launch of 4 rockets (fig. 3.3.2-1, left).
The loads during the launch occur at the moment when the rocket has just left the launcher tube and its propulsive jet hits the front launcher side. These loads are considerably higher than the recoil loads occuring during firing of the 0.5'' machine gun.
During the integration tests of the HMP/MRL 70 system on the BO105 experiences could be gained with the effect of blast overpressure of the machine gun. In the first tests series symmetric gun muzzles (fig. 3.3.2-3) were used. Thus, the blast overpressure could also impact onto the fuselage. It was so strong that it had some destructive effect on parts of the helicopter structure. The according flight test report reads as follows:

- overpressure pulses are uncomfortably sensed by the crew in the stomach and face (cheeks)
- the ashtrays were flung off the inner side of the doors
- during the MG salvos opening gaps between doors and frames of 15 mm could be observed
- windows in the doors on pilot and co-pilot side were cracked (see fig. 3.3.2-4)
- screws loosened on the sight unit
- artificial horizon on the instrument panel was defect after test

The problem could be completely solved with an asymmetric muzzle which directs the blast into the vertical direction away from the fuselage (see fig. 3.3.2-5). A theory and a model to estimate gunfire blast pressure is given in /18/.

Guided weapons require a certain precision concerning angular offsets of their own line-of-sight (LOS) with the one of the vision system (fig. 3.3.2-6). An important task during the on-ground commissioning of a guided weapon system is the static "harmonization" of these LOSs with a fixed airframe reference. This is accomplished by rather sophisticated optical measurement procedures.
The harmonization establishes the geometrical link in the fire control computation between the images seen by the missile optronics and the sight system. Interesting is now the question how the LOSs divert (in other words "dis-harmonize") in a flight situation compared to the adjustment on ground due to the structural deformations of the airframe. The effect of the steady state deformation on the LOSs could be compensated by factors in the fire control calculation. Therefore it is necessary to determine the disharmonization in prior development flight tests. This can be done with TV cameras mounted near the missile on the launcher, near the sight head and on an airframe reference point (see the photo of such a measurement on TIGER on a TRIGAT launcher in fig. 3.3.2-6). An evaluation of the synchronous, digitized TV pictures of all measurement stations allows the determination of the dis-harmonization. Disharmonizing effects on the airframe and weapon carrying structure originate from

- aerodynamic drag forces on launcher and sight head
- main rotor torque and mast bending in the case of a mast mounted sight
- load factor.

Also loads during malfunctions have to be considered in the process of weapon integration. An example is the hang-fire case, when the missile does not leave the launcher tube after ignition of the starter propulsion motor.
A simulation of such an event, in the frame of a safety investigation preparatory to a slug firing of STINGER (ATAS) on TIGER is shown in fig. 3.3.2-7. A "slug" is a special test ammunition with only a starter motor to experimentally investigate the complete STINGER functional chain with the launch process included. Also the separation of the STINGER missile from the launcher is investigated. The impulse of the starter motor (9000 N over 30 ms) is not problematic for the weapon carrier.

4. DYNAMICS, VIBRATION

4.1 Requirements Overview

Requirements for dynamic and vibrational behaviour of the helicopter/weapon system can be devided into those for aircraft airworthiness and for qualification of crew/troop comfort and equipment exposure to oscillatory accelerations.

4.1.1 Aircraft Airworthiness Requirements

The three following simple requirements of the FAR 29 could lead us to forget the development efforts, that a helicopter manufacturer has to invest, in order to present to the market a dynamically stable, low vibration vehicle design with competitive life cycle cost.

"Each part of the rotorcraft must be free from excessive vibration under each appropriate speed and power condition." (FAR 29.251)
"The rotorcraft may have no dangerous tendency to oscillate on the ground with the rotor turning." (FAR 29.241)
"Each part of the rotorcaft must be free from flutter under each appropriate speed and power condition" (FAR 29.629)

Distinct requirements for vibration levels (e.g. for comfort) are missing in the FAR. The general vibration requirement of the FAR has to be understood in the sense of an additional basic aircraft handling requirement. Aside these requirements, addressing the more gloabal vehicle dynamical behaviour, there are some more which are related to engine vibrations and critical shafting speeds.

4.1.2 Human Body Vibration Exposure Requirements

For the specification and assessment of vibrations at the crew stations several requirements are in use.
A general industrial one is the ISO 2631, which defines numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz, /21/. The limits are given for use according to the three generally recognizable criteria of preserving comfort, working efficiency and safety or health. The vertical (ref. aircraft) acceleration limits as r.m.s values versus frequency is shown in fig. 4.1.2-1. Depicted are the curves for the so-called "fatigue/decreased proficiency boundary". The values have to be multiplied by two to obtain the safety/health relevant "exposure limits" and respectively

have to be devided by 3.15 to obtain the "reduced comfort boundary". According limits exist the other two spatial directions.

Specially issued for rotorcraft is the ADS 27 /19/. The measured vibrational velocity frequency spectra in all 3 directions are normalized with specified values versus frequency. The four largest peaks (excluding the 1/rev peak due to main rotor unbalance) are geometrically summed to build a single charactistic value, the "Intrusion Index" (see fig. 4.1.2-2). Specifications for thresholds of this index are given in the ADS27 with relevance to rotorcraft flight states and measurement locations in the aircraft (pilot, weapon system operator, troop).

4.1.3 Equipment Vibrational Qualification Requirements

Well known are the military environmental specifications for aircraft equipment, the MIL-STD-810 D. A sub-part of this, the method 514.3 is relevant for equipment qualification with respect to helicopter vibrations. The basic, normalized spectrum shown in fig. 4.1.3-1 recognizes the rotor harmonics and a "noise" related power spectral density. In practice, the latter can get quite problematic in the case of structural resonances. The MIL-STD-810D provides vibration levels which have to be applied for equipment development and to be verified in the lab on vibration shakers. Anyhow, it also recommends the usage of vibration levels measured in flight test at the according component and thus leaves the way open to negotiate feasible solutions in cost and time between the equipment integrator and supplier.

4.2 Dynamics - Concepts

4.2.1 Rotor Systems

In the past 40 years rotor designs have experienced an evolution which is characterized by an application change from classical machine design elements over to sophisticated fiber structures. By this technology change, the classical flap, lead-lag hinges and also torsional bearings have been replaced by dedicatedly tailored bending and torsional softnesses in the continuum of the centrifugal retention ("blade neck" of hingless and "flexbeams" of bearingless rotors). Also spherical multi-functional elastomeric bearings providing the necessary blade motions of flapping , lead-lag and pitching, aside the centrifugal retention, are in use with today's hinged rotor hub designs.

All these efforts are aiming at the same goal: Reduction of number of parts, increase of fatigue life, reduction of wear and maintenance, in other words reduction of the rotor's contribution to the direct operating cost. Moreover operational safety is increased by the inherent load path redundance of composite structures. They have a slow and inspectable crack propagation and are (if properly designed) damage tolerant. An overview on modern main rotor hub and multifunctional blade CF retention designs (NH90, TIGER and ALH, EC135) is given in fig. 4.2.1-1.

Aside the basic carrying function the main rotor has to provide aircraft propulsion and control by blade tip-path plane tilt (thrust vector tilt and often also hub moment production). This is provided by the flapping degree-of-freedom (d.o.f) of the rotor blades in the centrifugal field in (nearly) resonance with the rotational frequency of the rotor. Due to Coriolis coupling and the aerodynamic loading in forward flight the main rotor blade must also have an inplane (lead-lag) d.o.f. Fundamental for the provision of these functions and the loads/vibrational behaviour is the choice of the flapping and inplane frequency of the blades. In fig 4.2.1-2 application oriented combinations of flapping with inplane blade frequencies are shown. The blade frequencies are normalized with rotational frequency.

Main rotors for the classical main/tail rotor helicopter architecture are situated in the lower left corner of this diagram

- <u>articulated</u> main rotors in the range
  1.01 - 1.12 relative flapping frequency and
  0.25 - 0.7 relative inplane frequency

- <u>hingeless and bearingless</u> main rotors in the range
  1.05 - 1.15 relative flapping and
  0.4 - 0.8 relative inplane frequency

Indicated are also in this trade-off chart the frequency locations for tail rotors

- see-saw type (with central flapping hinge, e.g. BO105, BK117) with relative flapping frequency $\omega_\beta/\Omega=1$ and being stiff inplane ($\omega_\zeta/\Omega\approx1.8$)

- 4-bladed bearingless stiff inplane ($\omega_\zeta/\Omega\approx1.5$) as flying on the ALH (HAL Corp., India).

Soft inplane main rotors are of the articulated or hingeless, bearingless type, sub-critically tuned in the blade lead-lag d.o.f. with respect to nominal rotor speed. For these rotor types special inplane damping requirements have to be considered in order to avoid ground and air resonance instabilities. The lower the inplane frequency, the higher is the according inplane blade damping required for stable operation.

For articulated rotors, having a typical inplane frequency range of 0.1-0.3Ω, blade dampers are mandatory. At hingeless and bearingless rotors the virtual lead-lag and flapping hinges are arranged at higher rotor radii ("higher hinge offsets") already by structural strength requirements (bending curvatures). By this, higher inplane frequencies of up to $0.8\omega_\xi/\Omega$ are here anyhow within the trend of the concept. On the other hand, the inplane frequency cannot deliberately be increased due to resonance amplification of blade lead-lag loads ($\omega_\xi/\Omega\rightarrow1$). Bearingless and hingeless designs require therefore special care in the structural design not to exceed significantly 0.75Ω. For hingeless and bearingless rotors a best compromise range for the inplane frequency placement seems therefore to be situated between $0.6 < \omega_\xi/\Omega < 0.8$ (fig. 4.2.1-3, left diagram).

Minimum dampings required are here for an example helicopter approx. 1 - 4 %. (Of course also landing gear properties in damping and stiffness and fuselage inertia have also taken into account.) The modal transmissibility of cyclic blade root lead-lag bending moments due to the 1/rev-moment excitation (TR_ξ) ranges between factors of 3 to 12.

For hingeless and bearingless main rotor configurations, flapwise soft blades with a fundamental flap bending frequency $1.05 < \omega_\beta/\Omega < 1.15$ are typically selected, distinguished from articulated rotor systems with a blade flap frequency below 1.04 Ω. Hingeless and bearingless rotors are able to transfer high cyclic control moments from the rotating system via the hub to the fixed system (then steady state mast moments). This can be seen in the right diagram of fig. 4.2.1-3 from the curve for the transmissibility of the cyclic blade root flapping moment TR_β. For the flight mechanically relevant damping moments about the helicopters roll and pitch axes a similar relation exists (example: steady state roll damping D_Φ of an example helicopter, dashed curve in fig.4.2.1-3, RH diagram). The high roll and pitch damping moments result in a fast and more direct control of the helicopter.

4.2.2 Frequency and Resonance Schedules, Forced Response and Stability

...Frequency and Resonance Schedules

With its rotary wings of main and tail rotor, the drive and transmission shafts, rotating masses of turbine disks, gear wheels and auxiliary aggregates, the helicopter is a conglomeration of rotating, oscillating, high energy machinery.

In each helicopter project a schedule is needed in which the possible coalescence of component natural frequencies and exciting rotational frequencies as well as multiples of them could be identified. Such a general schedule for standard helicopter architectures is shown in fig. 4.2.2-1.

There are some stringent requirements to avoid the frequency coalescence of rotational excitations and modes of the total vehicle and sub-structures, especially in the frequency range from zero up to the blade passing frequency n/rev. This is either necessary in order to provide dynamically stable aircraft operation (e.g. ground and air resonance, safety aspect) or to avoid resonances leading to vibrational discomfort for the crew and inadmissible oscillatory stressing of equipment. The image stabilization control in military visionics systems may get an unsolvable task with an unproper placement of main rotor blade bending natural frequencies or those of the sight structures.

... Forced Response

At nominal rotational frequency Ω, rotor blades as well as their hub attachments have to be designed with respect to stiffness and mass distribution such, that their bending and torsional natural (eigen-) frequencies should be well separated from the rotor harmonic frequencies $n\Omega$ and $(n\Omega \pm 1)$. This is necessary in order to avoid a resonance amplified transfer of harmonic excitational rotor loads from the rotating frame via the the hub into the fuselage structure. Otherwise unacceptable vibrations with the frequency $n\Omega$ could be expected.

One example where these frequency placement requirements are satisfyingly fulfilled can be seen in the frequency diagram for the TIGER main rotor in fig. 4.2.2-2. Depicted are here the natural frequencies for blade flap, lead-lag bending and torsion versus rotorspeed.

The effect of a modal blade tuning with additonal masses at different rotor radii can be seen in an example for the BK117 4-bladed main rotor (fig. 4.2.2-3). The application of these tuning masses had the desired effect of separating the frequency of the 2nd flapping mode from the 3/rev rotor harmonic excitation frequency (rotating system) , thus reducing the modal amplification factor for the 4/rev rotor harmonic in the fixed system.

... Anti-Resonance Systems for Vibration Reduction

Remaining $n\Omega$-vibration levels can be reduced by application of an anti-resonance system (see fig. 4.2.2-4). Well understood is, that those vibrations originate mainly from $(n\Omega \pm 1)$- roll and pitching hub moments in the rotating frame. Direct $n\Omega$-oscillatory vertical hub forces contribute less to vibrations.

Therefore the designs of e.g. the EUROCOPTER anti-resonance systems SARIB (as applied in TIGER) and ARIS (as applied in the EC135 helicopter) allow, aside a vertical, also for a rolling and pitching degree-of-freedom of the whole main rotor/ main gearbox (MGB) assembly. For the SARIB system this is made possible by a soft-in-bending, stiff-in-torque MGB mounting (diaphragm). Common to both systems is, that resonator masses, oscillating in the fundamental $n\Omega$-frequency against a spring system, combined with the MGB struts, effect an extinction of vertical and horizontal accelerations at the attachment points of the MGB struts. For this transmissibility notching the anti-resonance system is tuned by variation of the resonator masses. The transmissibility diagrams in Fig. 4.2.2-4 show this notch for the longitudinal and vertical acceleration per 1000 Nm pitch excitation hub moment at 21 Hz (tuning for TIGER) /24/, /27/.

...Stability, Ground and Air Resonance

Ground and air resonance are dynamic instabilities involving the coupling of the blade lead-lag motion with the inplane motion of the rotor hub /37/, /38/.

Hub motions in this context can either stem from

- roll and pitch oscillations of the airframe with landing gear on ground ("ground resonance")

or from

- coupled fuselage roll/pitch and rotor tilt motions (blade flapping) in flight ("air resonance").

These phenomena can only occur with soft inplane main rotors (lead-lag natural frequency $< 1\Omega$). Soft inplane tail rotors can have such destabilizing conditions with vertical modes of the fuselage/tailboom structure, being comparable to the ground resonance phenomenon of the main rotor.

Basic for the understanding of the instability is , that due to the lead-lag modal motion of all rotor blades the rotor center of gravity (CG) can experience an excentricity from the hub center (cyclic inplane rotor modes). There is a cyclic inplane rotor mode, which effects a slow progressive whirling motion of the complete rotor CG with the frequency $|\Omega-\omega_\zeta|$. This frequency is in the vicinity of the fuselage pitch and roll natural frequencies and can lead to destabilizing couplings, if there is not sufficient damping available either in the fixed or in the rotating system (landing gear dampers, blade lead-lag dampers or blade aerodynamic coupling damping). The low frequency mode is in some literature also called "driving mode", recalling the self-excited nature of this instability (not a "resonance" phenomenon) /22/, /38/.

In figs. 4.2.2-5 and -6, frequency charts are shown, in which the natural frequencies of the fuselage (body) pitch and roll modes are drawn together with the stability relevant low frequency $|\Omega-\omega_\zeta|$ rotor inplane mode versus the variation of rotorspeed.

It seems to be inherent in state-of-the-art helicopter architectures that the stability critical intersection points of the frequency curves are in the vicinity of the operational rotorspeed (see the marked circles for potential ground and air resonance).

Damping results of ground and air resonance tests (TIGER project) can be found in the ground and flight test related chapters 4.4 and 4.5 of this lecture.

4.3 Prediction Methods for Dynamic Behaviour

The prediction methods for the dynamic behaviour of the helicopter and its sub-systems should provide information to the following topics:

- natural frequencies and forced response of rotating and non-rotating systems, e.g.
  - .. bending and torsion of rotary wings in the centrifugal field
  - .. rotor modes with reference to the fixed system
  - .. critical shaft bending and torsion
  - .. fuselage and sub-structures like tailplane, vertical fin, weapon wings, weapon stores, sight systems, etc.

- aerodynamic excitations with respect to rotorharmonic content, vortex excitations of fuselage and sub-structures

- dynamic instability phenomena
  - .. isolated rotor blade instabilities (flap-lag-torsion)
  - .. stabilizing, destabilizing characteristica of aerodynamic forces and moments
  - .. ground, air resonance
  - .. whirl flutter (eg. for tilt rotors)
  - .. classical flutter of rotating and fixed system aeroelastic structures

A comprehensive overview on rotary wing dynamics with citation of all relevant literature is given in /1/.
In this lecture only rough outlines will be given on some basic methods.

4.3.1 Rotor Dynamics

Elementary is the task of the determination of eigenfrequencies and mode shapes for rotor blade bending and torsion (see fig.4.3.1-1, top sketch of rotorblade).
Here the transfer matrix method /25/ with extensions for the centrifugal field is in use. The rotor blade is devided into segments. The structure is described by massless beam elements having only stiffness properties and discrete masses (see fig. 4.3.1-1, middle). The describing state variables of the problem are the deflection, slope angle, moment and shear force. Variants of the transfer matrix method use general boundary/eigenvalue solutions of beam elements with distributed mass. Special know-how is needed to introduce into this method the boundary conditions for the hub attachment, additional spring elements, modelling elastomeric bearings or multiple load path structures for bearingless rotors having a flexbeam and a control cuff. An example of a transfer matrix scheme, modelling the hub arm, hub bearing and blade arrangement of the EC BO105 and TIGER is shown in fig. 4.3.1-1 (bottom sketch).
There are other methods to determine eigenfrequencies and mode shapes like the finite element method (FEM). Here, industrial standard structural FEM analysis codes like ANSYS or NASTRAN with extensions for modal analysis in the centrifugal field can be used (at least for uncoupled modes).
For higher harmonic response analyses of the rotor in his own complex non-uniform inflow environment, sophisticated semi-empirical models are used, describing the 3-dimensional flow field under/ behind the rotor due to its wake geometry.
This is interesting for the estimation of vibrations and vibratory hub loads transmission in the transition velocity range at 30-40 kts or for descent.
The result of a free wake simulation with the comprehensive rotorcraft analysis computer code CAMRAD/JA /26/ is shown in fig. 4.3.1-2 (top). The calculated induced velocity distribution in the rotor disc (polar diagrams on the LH side) according to to the simulated wake geometry (RH side) show good correlation with an according experiment.
Consideration of the wake geometry in the induced velocity calculation is the key for the prediction of higher harmonic hub/shaft loads as can be seen from an example for the EC135 on bottom of fig. 4.3.1-2.
A slight chance of estimating dynamic control pitch link loads, as they occur in high load factor flight, exists only when using a dynamic stall model for the aerodynamic lift and moment characteristics of the airfoil sections (fig. 4.3.1-2, mid diagrams). Applications of comprehensive rotorcraft analysis codes and comparisons with measurements are shown in /12/, /13/.

4.3.2 Dynamics of Fuselage and Sub-System Structures

Natural frequencies and mode shapes of the total fuselage and also sub-structures (tailplane, weapon wing with stores, antennae, etc.) are calculated by using the FEM.
An example from the NH90 project is shown in fig. 4.3.2-1. The number of degrees-of-freedom for the total NH90 FEM model amounts to approx. 22000.
The modeshapes are 3-dimensional which complicates their practical interpretation. It should be noted that predictions of complete fuselage natural frequencies and mode shapes are more or less only reliable in the range (say) up to 20 Hz. Higher frequencies and modes require for a prediction a hardly achievable modelization precision because the spatial structural expansions, relevant for the energy contribution in the higher frequency modeshape, are getting smaller and smaller.

4.4 Verification of Dynamic Behaviour - Ground and Flight Tests

Modal predictions for the complete fuselage can be verified by shake tests with the helicopter standing on ground and hanging in a rig, simulating the flight "free-free" boundary condition. A comparison between a calculated and a measured "free-free" mode shape gained by shake testing is shown for the TIGER prototype PT1 in fig. 4.4-1.
The rigid body modes of fuselage pitching and rolling for the helicopter standing on ground are also measured in the shake test and can directly be used to check the theoretical assumptions for the ground resonance test, which is a key event in the commissioning of a helicopter prototype. The practical performance of the ground resonance test consists of the excitation of the low frequency inplane rotor mode with the frequency $|\Omega - \omega_\zeta|$. This is done by the pilot, whirling the cyclic control stick progressively (in the sense of main rotor rotation) (see fig. 4.4-2, TIGER project, diagram on left top). The result of the pilot's excitation exercise should be seen in significant blade lead-lag modal motions with the frequency ω_ζ (fig. 4.4-2, LH diagram in the middle, blade lead-lag damper oscillations). When the pilot stops the excitation (the stick whirl) the blade lead-lag modal motions should vanish with a reasonable decay, thus demonstrating stable behaviour. From the evaluation of the decay the relative damping in can be calculated and documented versus rotorspeed in a damping diagram (fig. 4.4-2, TIGER project, right bottom). The same procedure holds for the performance of an air resonance test (see fig. 4.4-3, TIGER project). During the test the helicopter makes significant roll motions. Additionally to the decay behaviour of the modal blade lead-lag motions the decay of the helicopter roll rate is assessed for stability. Low air resonance roll damping can degrade steady level flight operations in gusty conditions (especially when vision systems are used).
Other flight tests related to dynamics deal with vibration (acceleration) measurements at the crew stations or interfaces and compartments of sensible equipment.
As an example a measurement of vibratory vertical cabin accelerations (4/rev) of the BO105 for level flight and flare is shown in fig. 4.4-4. Higher vibration levels are always encountered in the so-called speed transition range 30-50 kts and in high speed conditions. In this diagram also the vibration sources for each velocity range are explaned. Vibration generation is mainly due to blade vortex interactions at low

speeds as well in in flares and due to compressibility effects (dynamic stall) at the advancing blade in high speed flight.

4.5 Special Considerations for Weapon Systems

After the afore described tasks and activities to accomplish a satisfying stability and vibrational behaviour of the integral helicopter some examples of dedicated dynamic adaption problems of weapon systems may be mentioned.

External support structures for missile launchers, sight systems and guns or cannons have to be designed such that coalescence with multiples of the main rotor blade passing frequency should be avoided. Increased vibration due to resonance could severely affect the combined launcher/ missile functions before and during launch. Lock-on of fire-and-forget missiles can get problematic.

As an example for a design to this dynamic requirement a plot with the natural frequencies of the TIGER weapon stubwing in dependency of the mass of the inboard mounted TRIGAT launcher with a loading variation from empty to full (4 long range anti-tank missiles) is shown in fig. 4.5-1. On the outboard station of the stubwing the MISTRAL ATAM are attached. With decreasing mass (weapon delivery) on the inboard station there is no crossing of the 4/rev excitation frequency line for all wing degrees-of-freedom (for-aft, vertical, torsion).

An approach for dynamic qualification of helicopter stores and equipment is described in /28/.

Vibrations (or better: shock sequences) from cannons require a special isolation treatment of sensible equipment by using shock mounts. To get an impression of the accelerations in a helicopter cabin during gun firing, an according measurent of a fire-burst with the 0.5''-MG of the HMP on a BO105 is shown in fig. 4.5-2. A measurement of the true hight of the shock peaks is difficult because all possible frequencies of the structure in the neighbourhood of the accelerometer pick-up are excited. Elements for the protection of equipment or total sub-structures like instrument panels should be better selected by damping criteria for shock wave forms than for steady state vibration isolation.

5. ACOUSTICS

The noise emission of the helicopter is an important criterion for its mission suitability. The operation over urban areas with high population density is often restricted if not totally prohibited because of noise annoyance.

Also the effectiveness with respect to military missions suffers from the easy detectability over long distances. Aside the annoyance for the outside environment helicopters have also some shortcomings as concerns the interior cabin noise levels.

The following short overview on military helicopter acoustics is given with strong reference to /33/.

Basic information on helicopter noise is provided in /1/ and /34/.

5.1 Requirements Overview

Military helicopters are often operated for civil services in peace time, e.g. in EMS, SAR missions. In highly populated areas local authorities introduced restrictions to helicopter operations which are applied in some cases also to military helicopter bases.

Though civil noise certification regulations are not the main drivers for dedicated military helicopter design, the ICAO (Annex 16) and FAR 14 CFR 21 and 36 regulations should be mentioned here /40/. Mainly the maximum flyover noise level and the duration of the flyover are affecting the neighbourhood noise.

Military requirements , the MIL-STD-1294, /31/ and the DEF STAN 00-970, ch. 108, /30/ establish limits only for the interior noise for protection of troops and crew and to guarantee the communication between the operating personnel.

Detectability requirements, if any, are at most only stated as a desired quality feature in a development contract for a military helicopter. For the detectability the far field noise radiation and the low frequency noise emission is important.

Basic differences between military and civil noise requirements are outlined in fig. 5.1-1.

5.2 Noise Sources

..External Noise

Predominant sources for the external noise are the main and tailrotor. Air pressure fluctuations at the observer location caused by the aerodynamic loading of the rotary wings generate the rotational noise. This noise contribution is charactarized in the frequency spectrum by peaks built up by the main and tail rotor harmonics in a frequency range from 18 to 500 Hz (low frequency noise). The higher tail rotor harmonics are overlapping in the spectrum with discrete tones of the engine as well as of the main and tail rotor gearbox in the frequency range from 1000 to 2000 Hz. This is the frequency range near the maximum human aural sensitivity ("A" transmissibility characteristic). Another higher frequency contribution in the spectrum originates from the main rotor broad band noise (1000 to 4000 Hz) caused by aerodynamic shear forces and vorticity on the rotor blades and in their direct vicinity.

Other noise sources stem from main and tail rotor blade to blade tip vortex interceptions ("blade slap").

The noise spectrum, measured at a fixed reference position on ground, changes significantly with the flight condition, resp. manoeuver of the helicopter under observation. This is due to the noise dependency of the aerodynamic loading of the rotors and more important due to its momentary directional radiation characteristic (see fig. 5.2-1)

.. Interior Noise

An example of an interior noise spectrum is shown in fig. 5.2-2 (BK117). Intensity contributions in the audible frequency range mainly stem from the higher tail rotor harmonics and different transmission stages of the main gearbox as well as from cooling fans (ventilation, oil coolers, etc.).

5.3 External Noise - Detectability

There are four main effects which influence the acoustic detection probability: the spectral characteristics of the noise source, the sound radiation conditions concerning damping and absorption of the environment, the masking of the sound at the receiver by other noise sources and the spectral characteristics of the human ear or the noise detecting sensor.

Considering the unweighted acoustic radiated acoustic energy, helicopters in horizontal flight condition have their main noise emission in the low frequency range up to about 500 Hz. At these low frequencies, the damping effects during the sound propagation are very small and do not influence the sound radiation. The sound damping and absorption increases with frequency. Thus it is understandable that engine noise can only be perceived in the closer neighbourhood of the helicopter. The human ear is well susceptible to the pulsive noise radiating from the rotors in the frequency range between 100 and 500 Hz (see

fig. 5.3-1). Results of basic investigations on the aural detectability of helicopters can be found in /29/, /32/.

Both, the spectral characteristics of the helicopter noise and the propagation conditions in the environment may lead to very large detection distances up to 10 km under worst conditions.

Sound transmission losses due to vegetation and terrain absorption are greater than the effects of atmospheric absorption and make it desirable, from this viewpoint, to fly "in the nap of the earth".

5.4 Interior Noise

The MIL-STD 1294A provides detailed requirements for internal sound level control during development, testing and operational phases of the helicopter. Helicopters with a design gross weight lower than 9070 kg shall not exceed the noise levels as indicated in fig. 5.4-1. The measurements to provide compliance with this MIL-standard have to be conducted at each crew station. The flight conditions shall be hover and level flight. An attenuation by the crews flying helmets is not considered.

Internal noise design aims for crew and passengers, unprotected and protected with an MK4 series flying helmet are specified in the U.K. DEF STAN 00-970 ch. 108.

Further attenuation of internal noise directly at the crews ears can be attained by active noise control (ANC) headsets. This offers a cost and weight attractive alternative or reduction in effort for a sound proofing treatment of the cockpit. Especially in the low frequency region up to 500 Hz an ANC headset provides more attenuation than a standard flying helmet.

5.5 Options for Noise Reduction

For noise reduction there exist options for design parameters like the main rotor blade area, tip speed or design take-off weight. Engine controls with variable rotorspeed offer an interesting operational parameter aside the flight speed to directly influence noise emisison (see fig. 5.5-1). Variations of flight speed and main rotor blade tip speed show the most significant effect in noise intensity change.

Other options refer to the choice of helicopter architectural features like the anti-torque device: classical tail rotor, FENESTRON or NOTAR.

A consequent helicopter design to low noise is the EC135 which incorporates a FENESTRON anti-torque fan-in-fin with unevenly spaced blades distributed over its perimeter. The second feature in favour to low noise emission is the variable rotorspeed from 100 to 104 %, which is controlled by altitude (100 % below 5000 ft, 104 % above 10000 ft with a transition in between these altitudes). The success of all the noise reduction measures as applied on the EC135 is demonstrated in fig. 5.5-2. The EC135 T at a take-off mass of 2700 kg has a sound exposure level lying below the ICAO Annex 16, Ch.11 requirements with a margin of 7 db. Also remarkably reduced is the aural detectection distance compared to an older helicopter design (BO105) (see fig. 5.5-3).

6. CONCLUSIONS

Function and reliability of weapon systems sensibly depend of the proper application of rules for the helicopter structural design. The crews concentration on the mission can be hampered by a noisy, vibratory cockpit or by steady load limiting warnings. Many algorithms in the weapon system software are based on informations with relevance to the helicopter mechanics. A mission success is questionable with higher probability of aural detectability caused by high noise emission.

The technology areas of loads and dynamic/vibration mechanics as well as acoustics therefore deserve increased attention in the development process of a helicopter weapon platform.

The aim of this lecture was to provide a view over the related requirements, conceptual options and methods.

Acknowledgements

The author wants to express his thanks to his colleagues in EUROCOPTER for the contribution of material:
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Literature

1. W. Johnson, "Helicopter Theory", Dover Publications Inc., 1994

2. G.D. Padfield, "Helicopter Flight Dynamics", Blackwell Science, 1996

3. U.S. Federal Aviation Administration (FAA), "FAR Part 29 - Airworthiness Standards: Transport Caregory Rotorcraft", incl. Amdt. 29-22

4. U.S. Department of Defense, "Structural Design Requirements, Helicopters" Military Specification MIL-S-8698 (ASG), July 1954

5. U.S. Munitions Board Aircraft Committee, "Ground Loads", ANC-2 Bulletin

6. U.S. Department of Defense, "Light Fixed and Rotary-Wing Aircraft Crash Resistance" , Military Standard MIL-STD-1290A (AV), September 1988.

7. U.S. Department of the Navy,"Structural Design Requirements (Helicopters)", Aeronautical Requirements AR-56, February 1970.

8. G. Reichert, "The Impact of Helicopter Mission Spectra on Fatigue", *in* "Specialists Meeting on Helicopter Design Mission Load Spectra", AGARD-NATO CP-206, April 1976, Paper 2.

9. G.L Martin and R.B. Johnson, "US Air Force Helicopter Operational Flight Spectra Survey Program -Past and Present", *in* "Specialists Meeting on Helicopter Design Mission Load Spectra", AGARD-NATO CP-206, April 1976, Paper 4.

10. AGARD WG on Helicopter V/STOL Structures and Dynamics, "Specialists Meeting on Helicopter on Rotor Loads Prediction Methods", AGARD-NATO CP-122, August 1973.

11. P.R. Edwards, J. Darts, "Standardised Fatigue Loading Sequences for Helicopter Rotors (HELIX and FELIX)", Fraunhofer-Institut für Betriebsfestigkeit Darmstadt Report No. FB-167, 1985.

12. L. Dadone, F.Caradonna, K. Ramachandran, M. Silva, D. Poling, "The Prediction of Loads on the Boeing Helicopters Model 360 Rotor", 45th AnnualForum of the American Helicopter Society, Boston MA - USA, May 22-24, 1989.

13. G.K. Yamauchi , R.M. Heffernan, M. Gaubert, "Correlation of SA349/2 Helicopter Flight Test Data with a Comprehensive Rotorcraft Model", 12th European Rotorcraft Forum, Paper n°74, Garmisch-Partenkirchen - Germany, September 22-25 1986.

14. M.S. Torok, D.T. Ream, "Investigation of Empennage Airloads Induced by a Helicopter Main Rotor Wake", the American Helicopter Society 49th Annual Forum,St. Louis, MO - USA, May 19-21 1993.

15. D. Nitschke, R. Müller, "Systematic Development of Crash Worthiness of the NH90", Second International KRASH User's Seminar, Cranfield, England, 26-28 June 1995

16. J.K. Sen, A.O. Bolukbasi, N.A. Chase, "Test and Analysis of an Advanced Technology Landing Gear", Journal of the American Helicopter Society, 37, 3, pp 42-52, July 1992

17. AGARD Flight Mech. Panel, WG 15, "Integration of Externally Carried Weapon Systems with Military Helicopters", AGARD-NATO Advisory Report No. 247, 1990

18. R.M. Hunt, A.J. Perry, S.A. Moorse, "Gunfire Blast Pressure Predictions", Royal Aircraft Establishment, Tech. Memo Aero 1801, August 1981.

19. U.S. Army Aviation Systems Command, "Requirements for Rotorcraft Vibration Specifications, Modelling and Testing", Aeronautical Design Standard ADS-27, June 1993.

20. U.S. Department of Defense, "Method 514.3, Vibration", Military Standard MIL-STD-810D, July 1983.

21. International Organization for Standardization, "Evaluation of human exposure to whole-body vibration - Part1 : General Requirements", ISO 2631/1-1985 (E).

22. H. Strehlow, D. Teves, G. Polz, "Applied Helicopter Aeroelastics - Modelling and Testing", 22nd European Rotorcraft Forum, Brighton - UK, 1996

23. H. Strehlow, B. Enenkl, "Aeroelastic Design Considerations in the Development of Helicopters", AGARD-NATO, 56th Structures and Material Panel Meeting, London, U.K., 1983

24. H. Strehlow, R. Mehlhose, P. Znika, "Review of MBB's Passive & Active Vibration Control Activities", Aero Tech 92 Conference, Birgmingham UK , 14-17 January 1992.

25. E.C. Pestel, F.A. Leckie, "Matrix Methods in Elastomechanics", McGraw-Hill, 1963

26. W. Johnson, "Development of a Comprehensive Analysis for Rotorcraft I, II.", Vertica, Vol.5, (I) pp. 99-129, (II) pp. 185-216, 1981

27. T. Krysinski, G. Seitz, "Overview of TIGER Dynamics Validation Program", 48th Annual Forumof the AHS, Washington, June 1992

28. D. Braun, J.Stoppel, "Approach in Dynamic Qualification of Light Helicopter Stores and Equipments" *in* "Dynamic Environmental Qualification Techniques", AGARD-NATO, CP No. 318.

29. J.B. Ollerhead, "Helicopter Aural Detectability", USAAMRDL Technical Report 71-33, Fort Eustis,Virginia, July 1971.

30. U.K. Ministry of Defence, "Internal Noise", Chap. 108, DEF STAN 00-970, October 1986.

31. U.S. Department of Defense, „Acoustical Noise Limits in Helicopters", Military Standard MIL-STD-1294A, August 1985.

32. R.G. Loewy, "Aural Detection of Helicopters in Tactical Situation", Journal of the AHS, October 1963, pp 36-53.

33. G. Niesl, G. Arnaud, "Reduction of the Noise Signature of the Eurocopter EC135", AGARD-NATO Flight Vehicle Integration Panel , Symposium on Advances in Rotorcraft Technology, Ottowa - Canada, 1996.

34. V. Langenbucher, E. Laudien, V. Klöppel, "Lärmerscheinungen bei Hubschraubern", Carl-Cranz Gesellschaft e.V. CCG Kurs Hubschrauber-Berechnung F2.03

35. U.S. Army Aviation Systems Command, "Handling Qualities Requirements for Military Rotorcraft", Aeronautical Design Standard ADS33C, August 1989

36. J.B. de Jonge, "Counting Methods for the Analysis of Load Time Histories", National Aerospace Laboratory NLR SB 80/106/U NLR, Netherlands, 1980

37. R.P. Coleman, A.M. Finegold, "Theory of Self-Excited Mechanical Oscillations of Helicopter Rotors with Hinged Blades", NACA Report No. 1351, 1958

38. R.T. Lytwin, W. Miao, W. Woitsch, "Airborne and Ground Resonance of Hingeless Rotors", 26th Annual Forum of the American Helicopter Society, June 1970

39. ICAO Environmental Protection, Annex 16, Vol. 1, Aircraft Noise, 11. Nov. 1993

40. U.S. Federal Aviation Regulation 14 CFR Part 21 and 36

FAR 29 Subpart C - Strength Requirements	
General	
§ 29.301	Loads
§ 29.307	Proof of structure
Flight loads	
§ 29.321	Flight loads - General
§ 29.337	Limiting manoeuvering load factor
§ 29.339	Resultant limit manoeuvering load factor
§ 29.341	Gust loads
§ 29.351	Yawing conditions
§ 29.361	Engine torque
Control surface and system loads	
§ 29.391	General
§ 29.395	Control system
§ 29.401	Auxiliary rotor assemblies
§ 29.403	Auxiliary rotor attachment structure
§ 29.413	Stabilizing and control surfaces
Main component requirements	
§29.547	Main rotor structure
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Fatigue evaluation	
§29.571	Fatigue evaluation of flight structure
MIL-S-8698 Chapter 3.2 Flight and Take-Off Loading Conditions	
chapter 3.2.1	Flight load parameters
chapter 3.2.2	Symmetrical flight
chapter 3.2.3	Unsymmetrical flight
chapter 3.2.4	Autorotationnal flight

Fig. 3.1.1-1: Flight load requirements /3/,/4/

No.	Landing case LIMIT LOAD CONDITIONS	Lift to Weight ratio	Vertical velocity	Attitudes and *Loads* - Regulations		
				FAR 29	MIL-S-8698	ANC-2
L1	Obstacle reaction main l.g. (2m)	2/3	2.44		3.4.5.1 *3.4.5.1*	
L2	Obstacle reaction nose l.g. (1n)	2/3	2.44		3.4.5.2 *3.4.5.2*	
L3	Nose down landing (1n)	2/3	2.44		3.4.5.3 *3.4.5.3*	
L4	Tail down landing (2m)	2/3	2.44		3.4.5.4 *3.4.5.4*	
L5	Tail down landing (2m)	2/3	2.44	29.481 (a)		2.313 *2.21 2.22*
L6	Maximum vertical reaction and drag reaction (2m)	2/3	2.44	29.481 (a) *29.479(b)(1;2)*		2.313 *2.23*
L7	Maximum spin-up and Dynamic spring-back (3mn)	2/3	2.44		*3.4.5*	2.311 *2.21 2.22*
L8	Maximum vertical reaction and drag reaction (3mn)	2/3	2.44	29.479(a)(1) *29.479(b)(1;2)*		2.311 *2.23*
L9	Maximum spin-up and Dynamic spring-back (2m)	2/3	2.44		*3.4.5*	2.312 *2.21 2.22*
L10	Maximum vertical reaction and drag reaction (2m)	2/3	2.44	29.479(a)(2) *29.479(b)(1;2)*		2.312 *2.23*
L11	Maximum spin-up and Dynamic spring-back (1m)	2/3	2.44		*3.4.5*	2.314 *2.21 2.22*
L12	Maximum vertical reaction and drag reaction (1m)	2/3	2.44			2.314 *2.23*
L13	Maximum vertical reaction (1m)	2/3	2.44	29.483 *29.483(a;b)*		
L14	Drift landing (2m)	2/3	2.44	29.485 *29.485(1)*		2.315 *2.315*
L15	Drift landing (3mn)	2/3	2.44	29.485 *29.485(2)*		

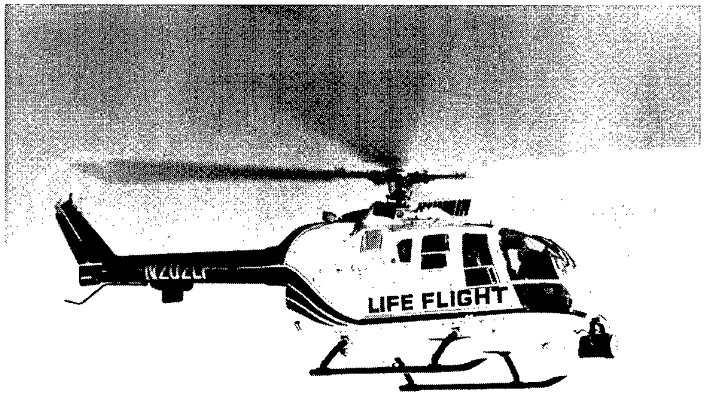
(x=1,2,3)n : x point(s) nose landing gear ; (x=1,2,3)m : x point(s) main landing gear.
(x=1,2,3)mn : x point(s) main and nose landing gear

Fig. 3.1.2-1 : Limit load conditions for landing gear (normal landing, nose wheel type) /3/,/4/,/5/

Condition number	Impact direction (aircraft axes)	Object impact	Velocity change Δv (ft/sec)
1	Longitudinal (cockpit)	Rigid vertical barriers	20
2	Longitudinal (cabin)		40
3	Vertical *	Rigid horizontal surface	42
4	Lateral, type I		25
5	Lateral, type II		30
6	Combined high angle * Vertical		42
	Longitudinal		27
7	Combined low angle Vertical	Plowed soil	14
	Longitudinal		100

* For the case of retracted landing gear the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 26 ft/sec

Fig. 3.1.2-2: MIL-STD-1290 Crash impact design conditions (landing gear extended) /6/



BO105

NH90

TIGER

Fig. 3.2.1-1: Different architectures and missions - Different flight and ground loads, BO105, NH90 and TIGER

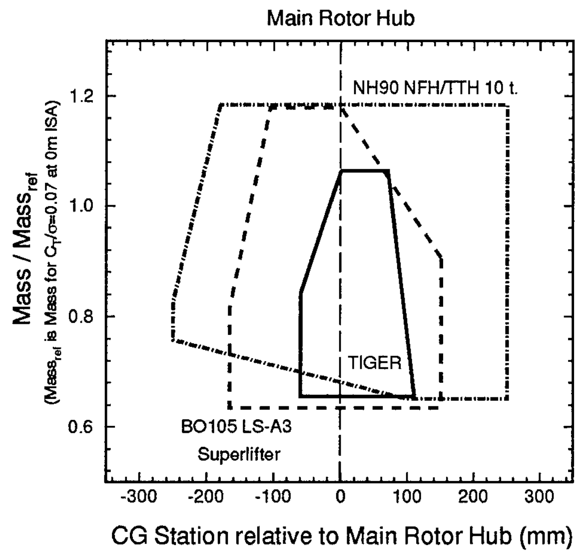


Fig. 3.2.1-2: Relative mass - C.G. differences for BO105, NH90, TIGER

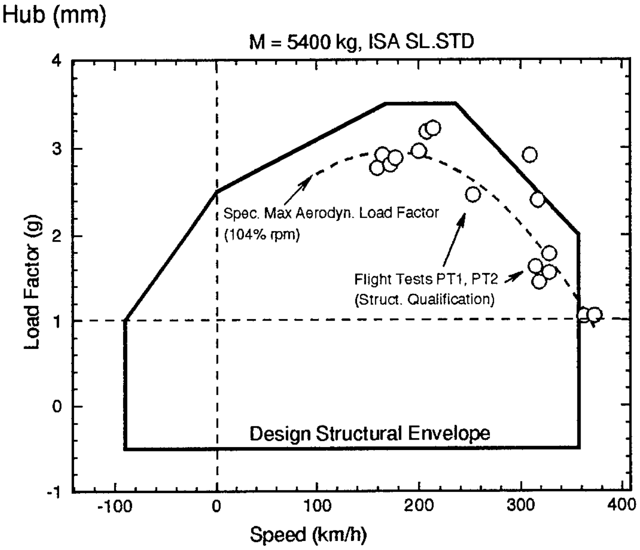
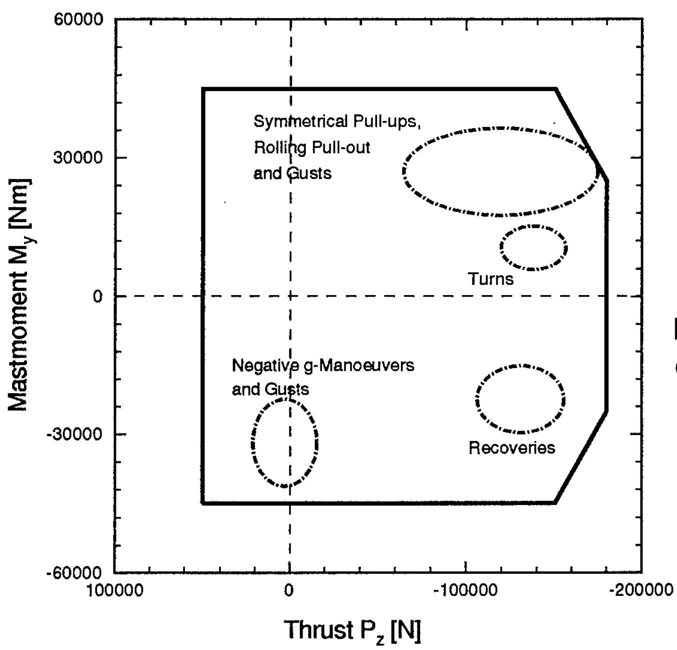


Fig. 3.2.1-3: Load factor - speed envelope for TIGER



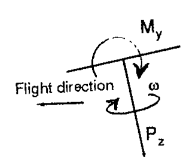


Fig. 3.2.1-4: Thrust - mast moment envelope for TIGER

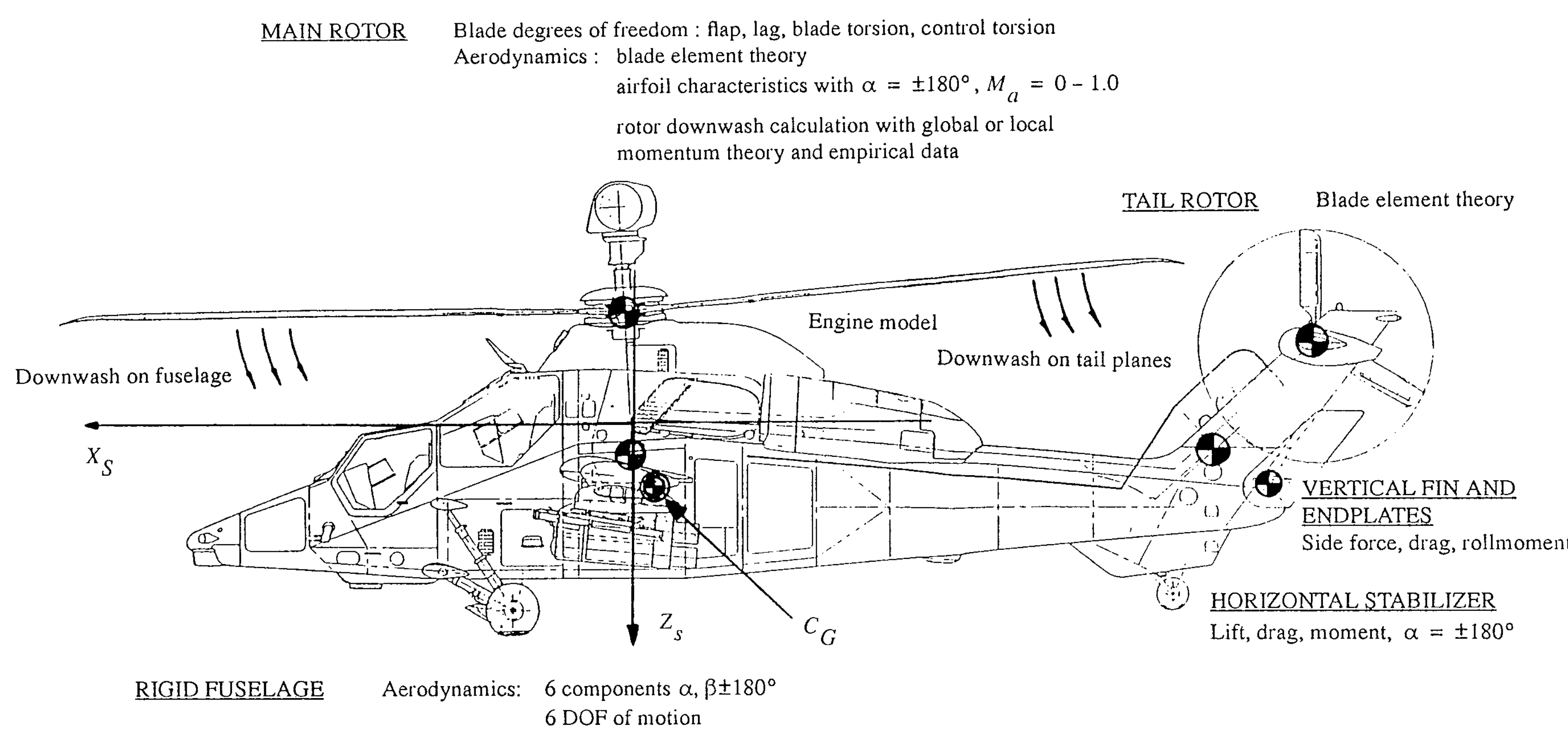
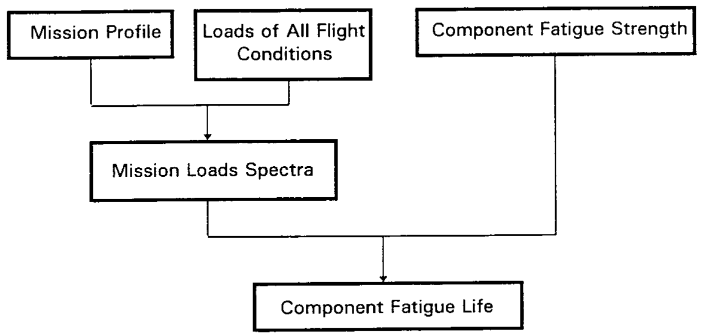
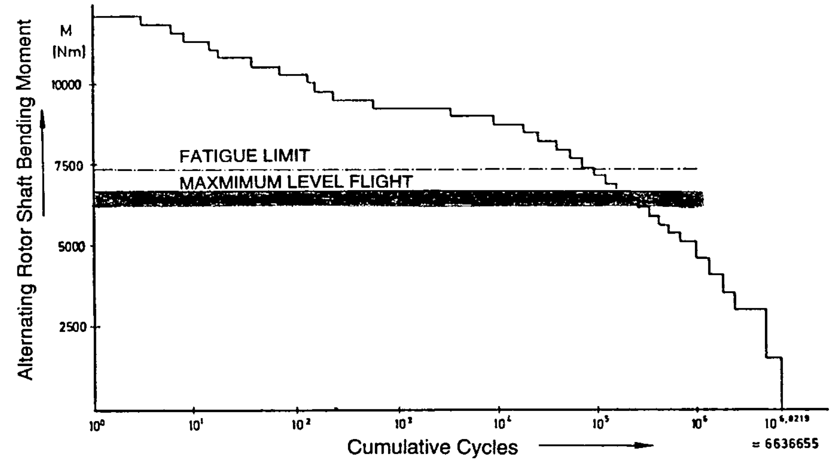


Fig. 3.2.1-5: Features of flight loads simulation model



Fatigue loads evaluation methodology

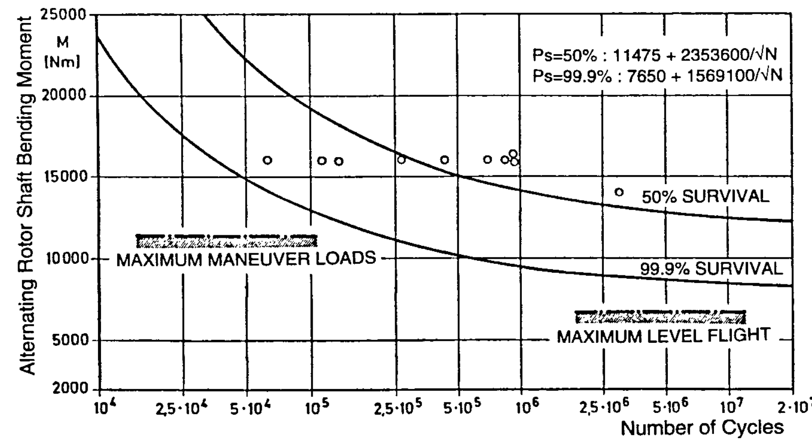


Cumulative load cycles and load levels

Ground conditions :	
Rapid increase of rpm on ground to quickly engage clutch	0.5
Taxiing with full cyclic control	0.5
Jump takeoff	0.5
Hovering :	
Steady hovering	0.5
Lateral reversal	1.0
Longitudinal reversal	1.5
Rudder reversal	1.0
Forward flight power on :	
Level flight, 20 % V_{NE}	5.0
Level flight, 40 % V_{NE}	10.0
Level flight, 60 % V_{NE}	18.0
Level flight, 80 % V_{NE}	18.0
Maximum level flight (but not greater than V_{NE})	10.0
V_{NE}	3.0
111 % of V_{NE}	0.5
Right turns	3.0
Left turns	3.0
Climb (max continuous power)	4.0
Cyclic and collective pull-ups from level flight	0.5
Change to autorotation from power-on flight	0.5
Partial power descent (including condition zero flow through rotor)	2.0
Landing approach	3.0
Lateral reversals at V_H	0.5
Longitudinal reversals at V_H	0.5
Rudder reversals at V_H	0.5
Climb (takeoff power)	2.0
Autorotation-power off :	
Steady forward flight	2.5
Right turns	1.0
Left turns	1.0
Lateral reversals	0.5
Longitudinal reversals	0.5
Rudder reversals	0.5
Cyclic and collective pull-ups	2.0
Landings (including flares)	2.5

	100.0

Flight state spectrum



Component fatigue strength (Wöhler curve)

Fig. 3.2.1-6: Procedure and elements of fatigue loads evaluation methodology /8/

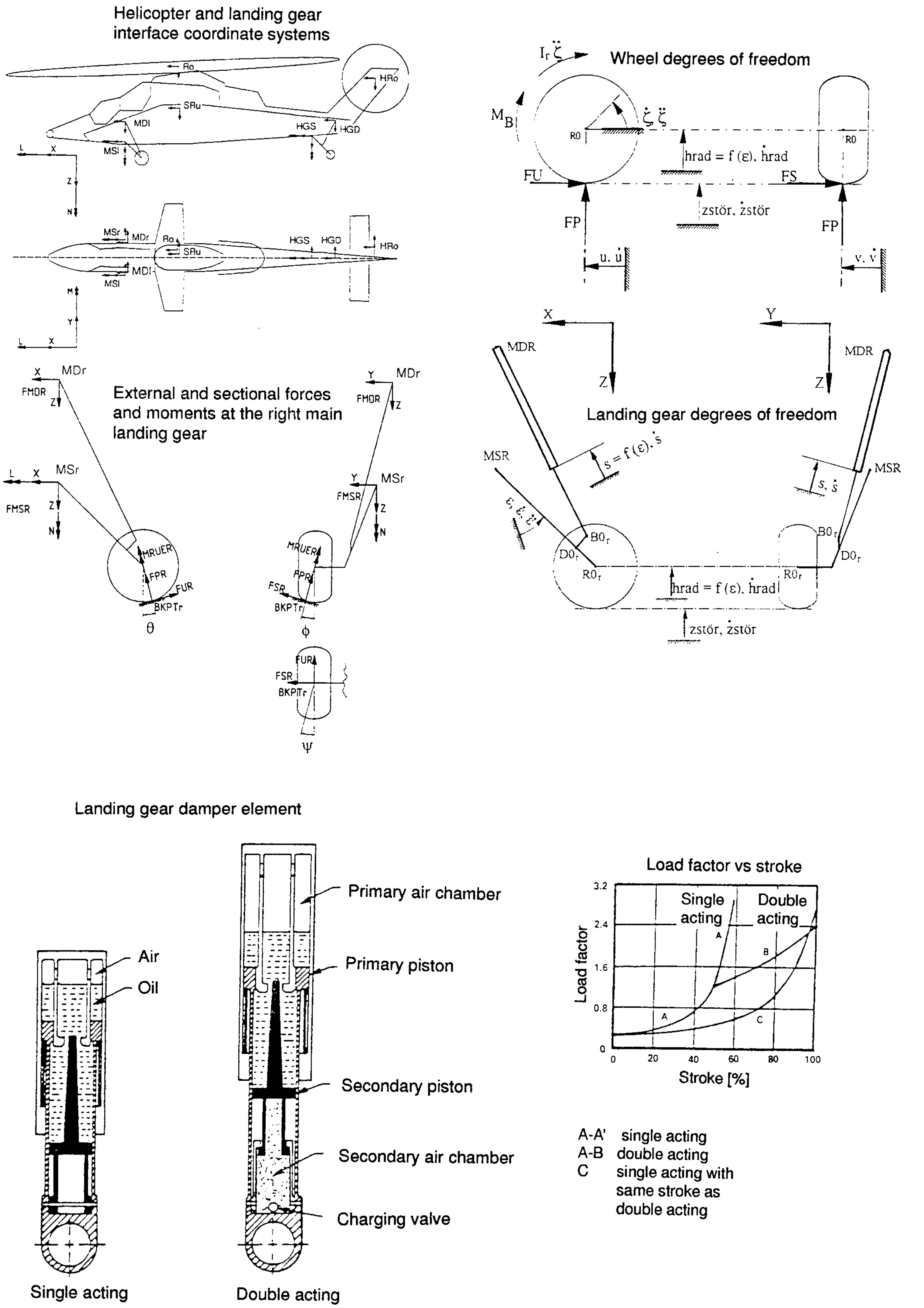
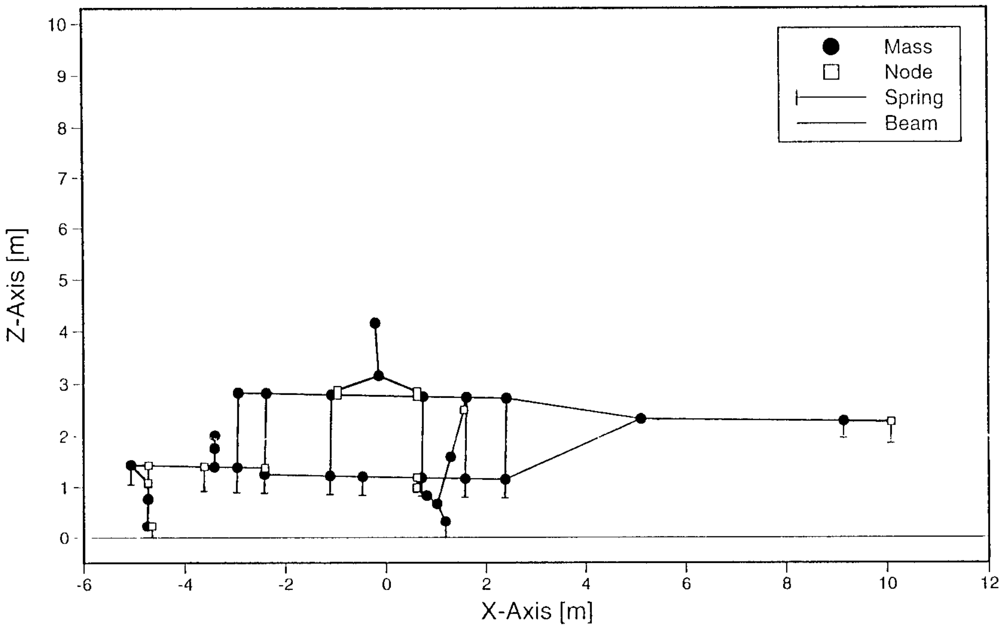


Fig. 3.2.2-1: Features of landing and ground loads simulation model

CONFIGURATION: NH90, m=8700 kg, $X_{CG} = 7.24m$, $Z_{CG} = 2.10m$,
$L/W = 1$, $V_z = 11m/s$, 3-PL, new LL NH90HNL4

Time 0.0 [s]



Time 0.1225 [s]

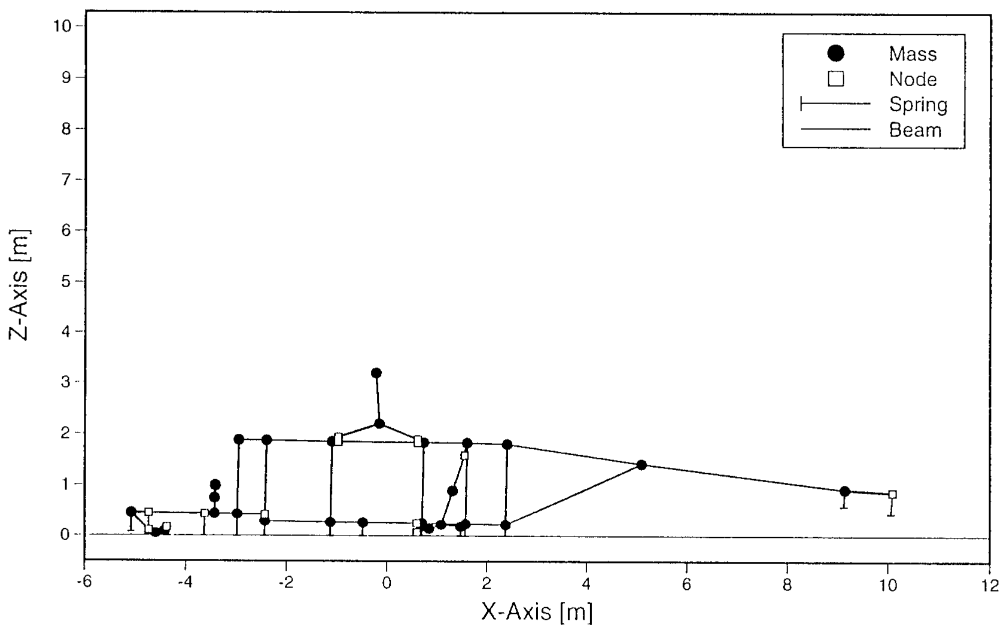


Fig. 3.2.2-2: NH90 crash landing simulation (model KRASH) /15/

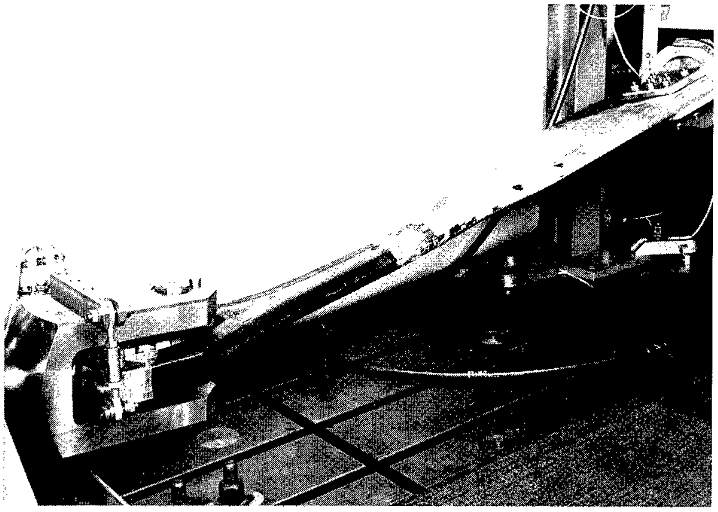


Fig. 3.2.3-1: Loading test of TIGER main rotor blade integrated neck and CF retention lug structure

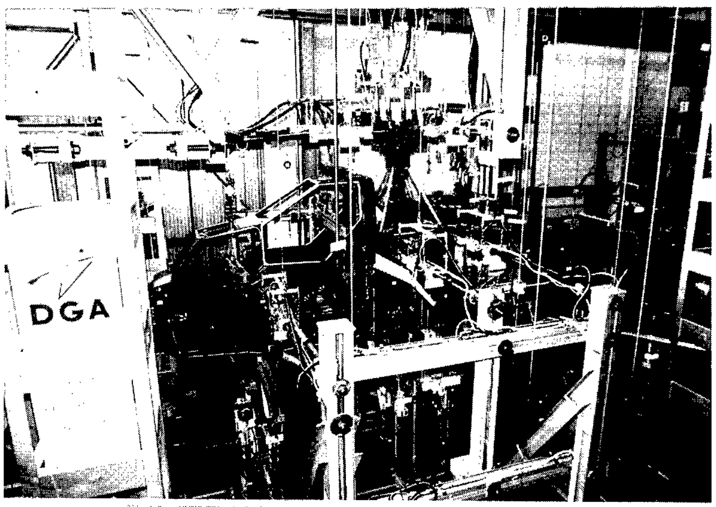


Fig. 3.2.3-2: Fatigue and limit load test of TIGER fuselage

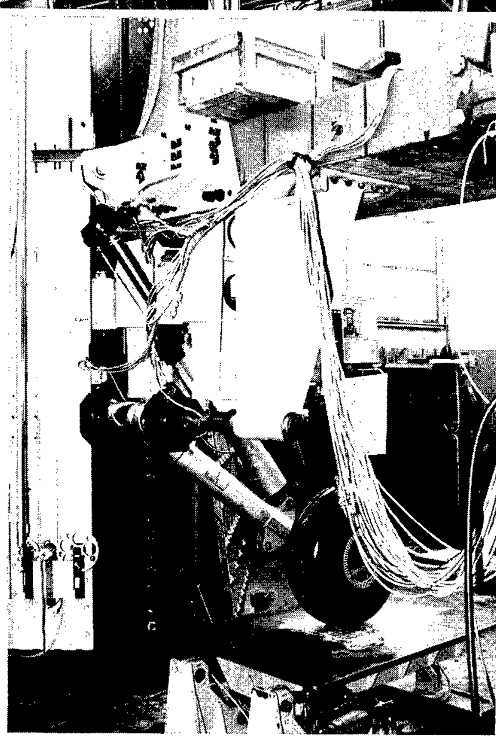


Fig. 3.2.3-3: Drop test with TIGER landing gear

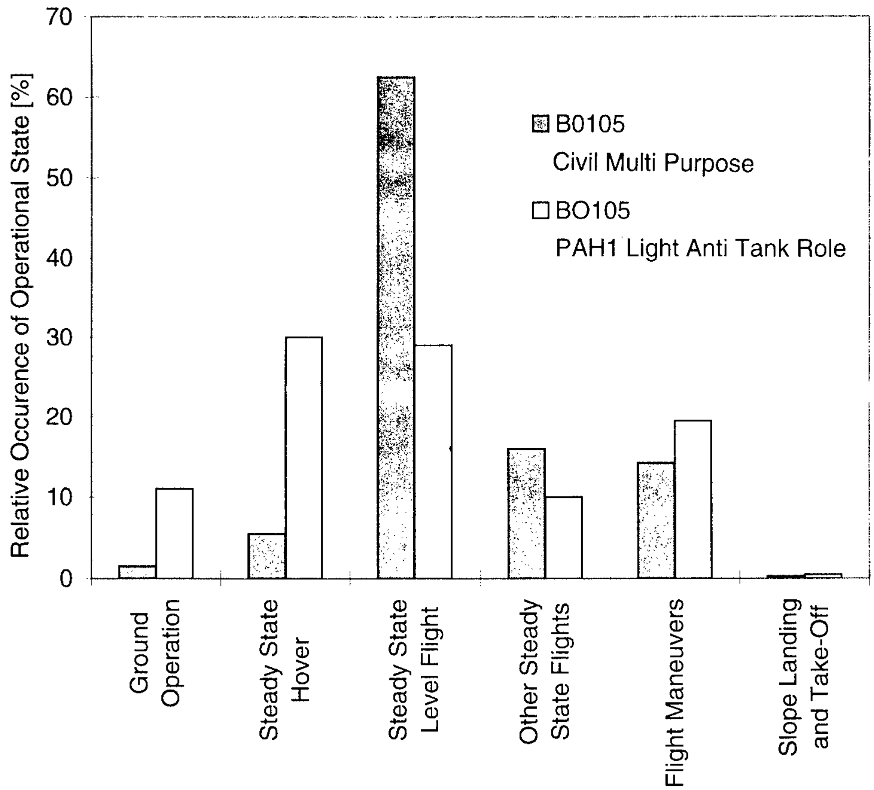


Fig. 3.3.1-1: Comparison of a civil and military mission spectrum

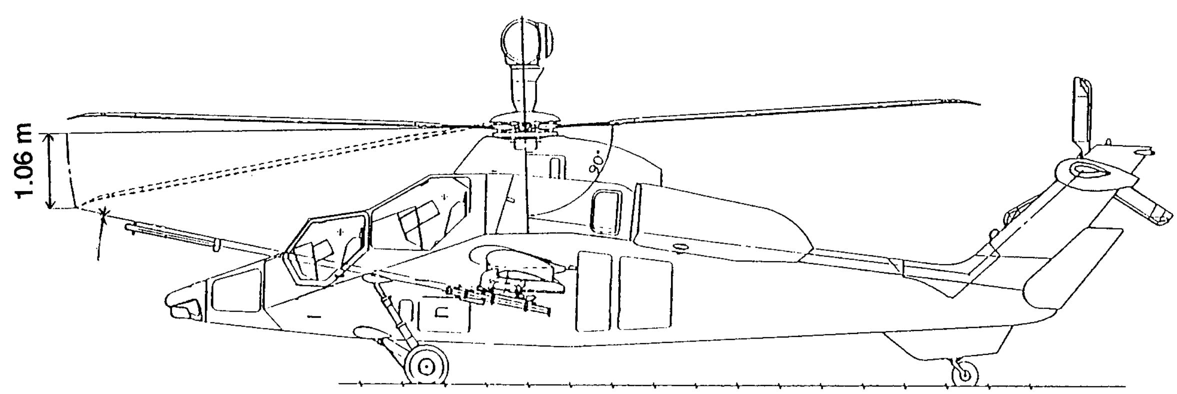


Fig. 3.3.1-2: Main rotor blade and missile flight path clearance check study

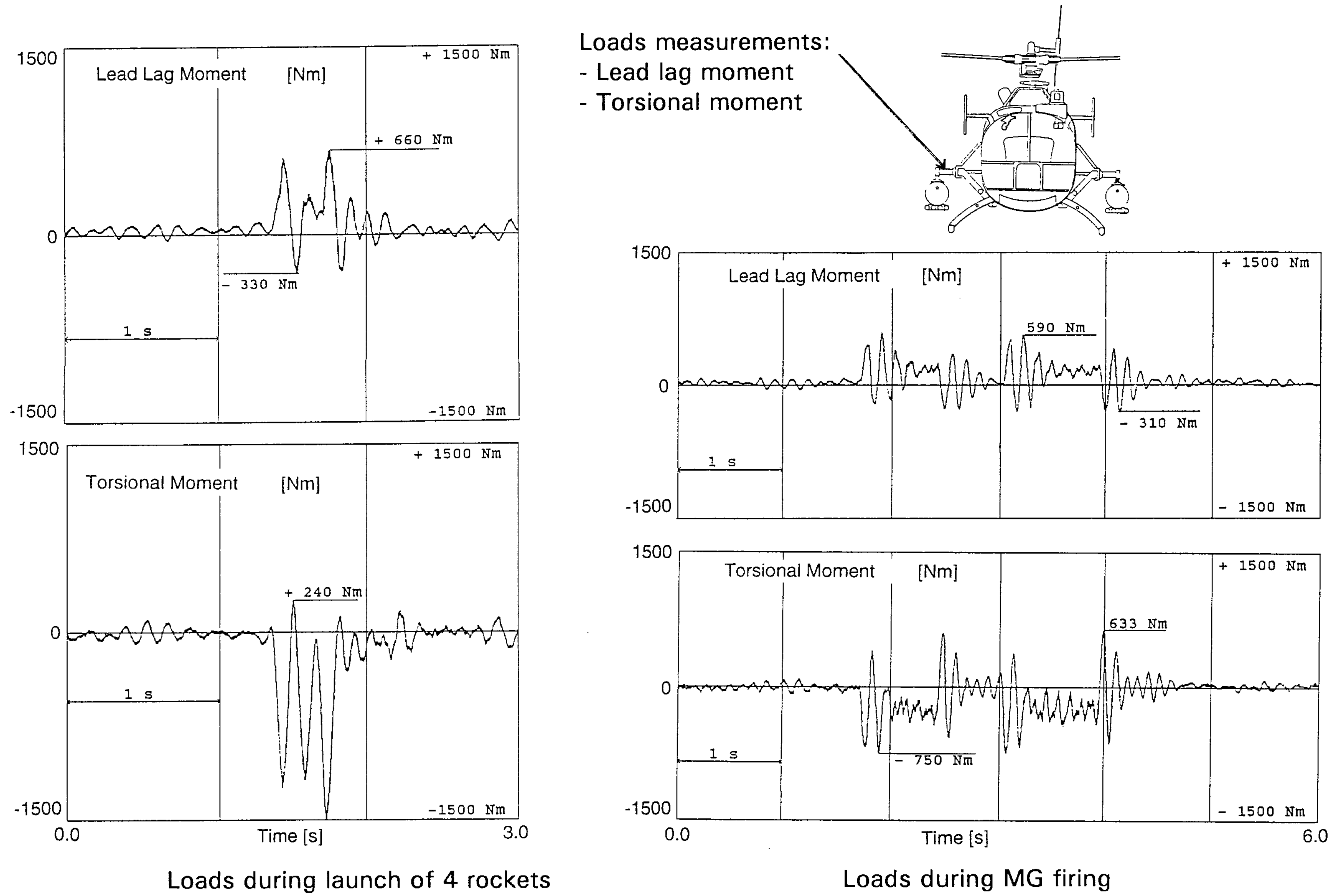


Fig. 3.3.2-1: Loads on a BO105 weapon suspension during rocket launching and MG firing

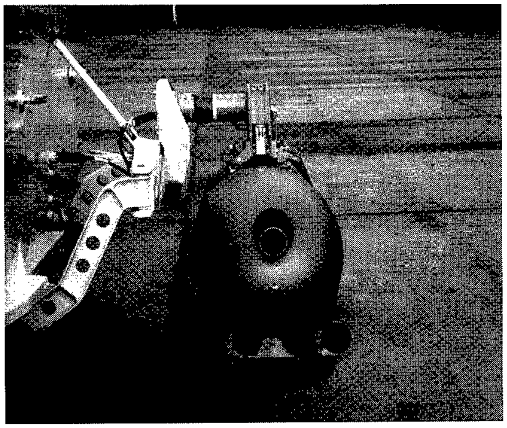


Fig. 3.3.2-2: Combined launcher gun pod HMP (0.5") / MRL70 (2.75")

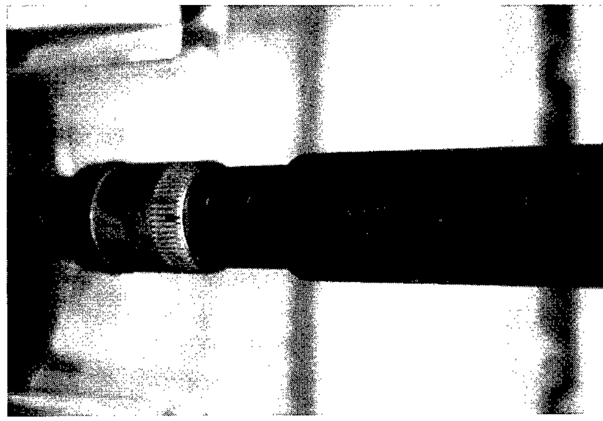


Fig. 3.3.2-3: Symmetric muzzle of 0.5" machine gun HMP

Fig. 3.3.2-4: Cracked cabin door window due to gun blast overpressure

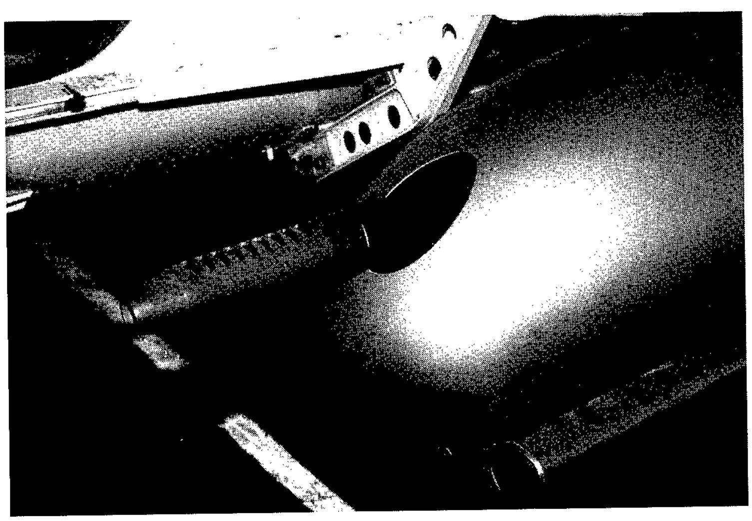
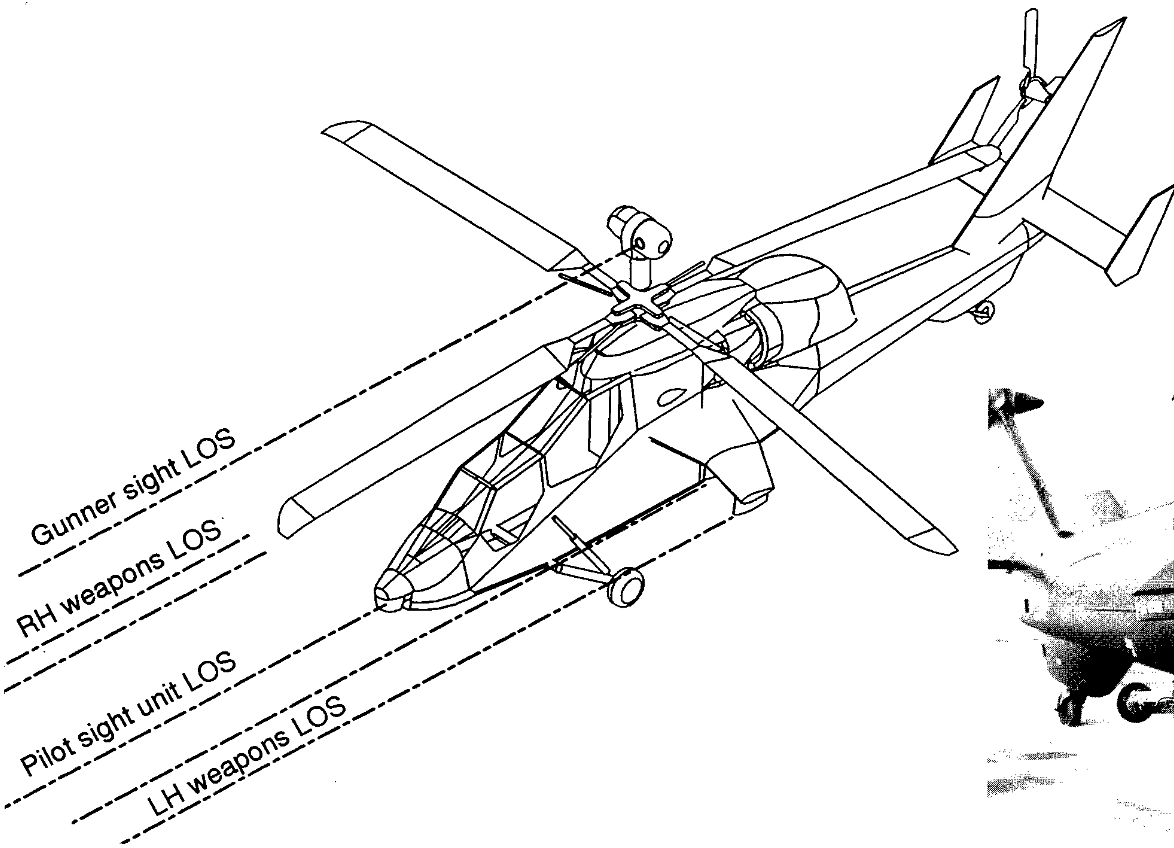
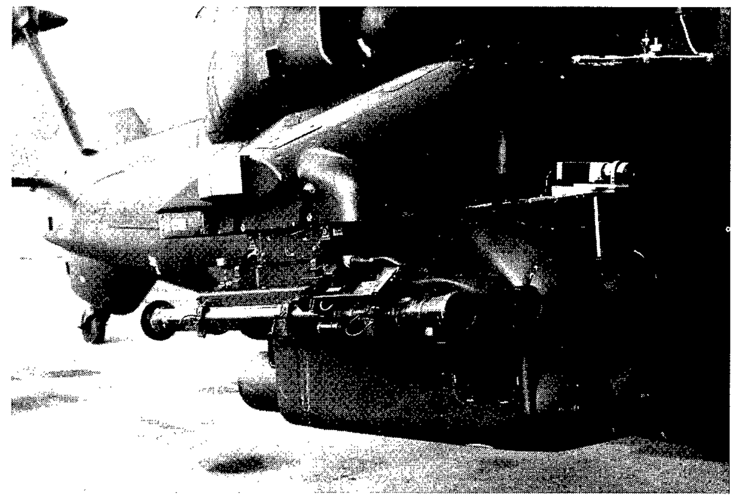


Fig. 3.3.2-5: Asymmetric gun muzzle to protect fuselage from blast overpressure





TV camera attached on TIGER TRIGAT launcher
to measure in-flight disharmonization

Fig. 3.3.2-6: Line of sights (LOS) for weapon stations and visionics on a combat helicopter

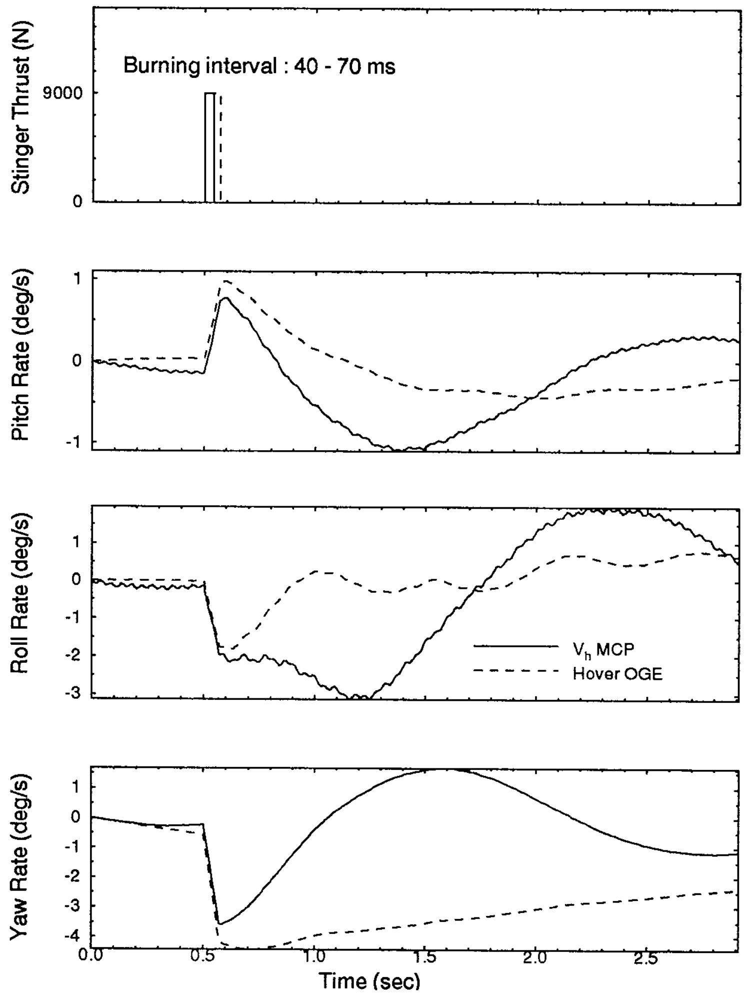


Fig. 3.3.2-7: Simulation of a STINGER slug hang fire case (hover OGE and level flight with V_h)

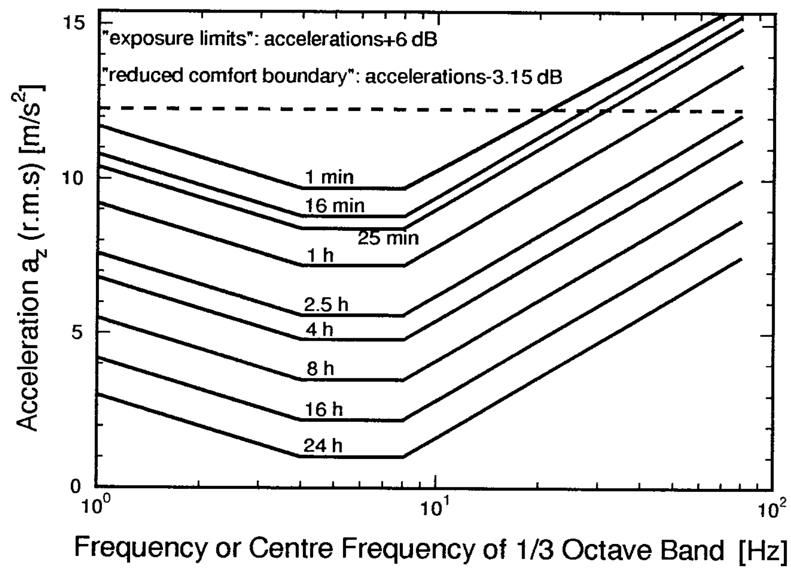
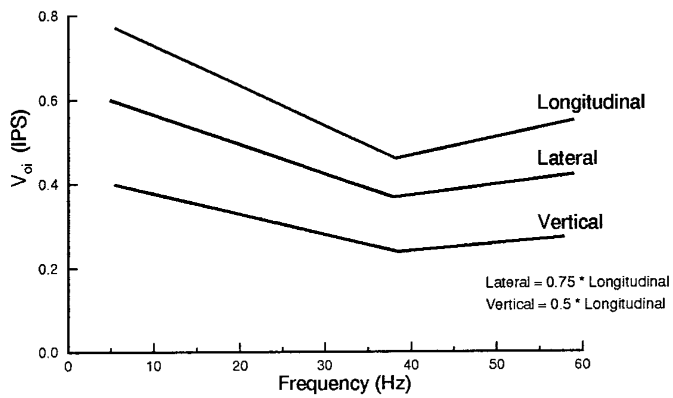


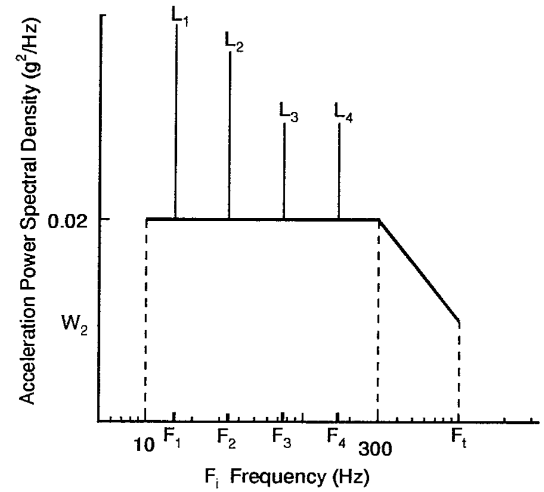
Fig. 4.1.2-1: Vibration exposure limits in the vertical axis of the human body according to ISO2631, /21/



Flight Condition	Location					
	Pilot		Weapon Sytem Operator		Troop	
	Intrusion Index I	1/rev (IPS)	Intrusion Index I	1/rev (IPS)	Intrusion Index I	1/rev (IPS)
Region I - steady flight : V cruise - 0.75 < nz < 1.25 g	1.2	0.15	1.0	0.15	2.0	0.15
Region II - maneuvers outside of Region I with duration > 3 sec	3.0	0.3	2.5	0.3	5.0	0.3
Region III - maneuvers outside of Region I with duration < 3 sec	4.0	0.4	3.0	0.4	6.0	0.4
Region IV - only applicable for tilt rotor	1.0	0.15	0.8	0.15	1.5	0.15
Weapons Firing Increment All Regions	+2.0	0.0	+2.0	0.0	+3.0	0.0

$$\text{Intrusion Index } I = \sqrt{\sum_{X,Y,Z} \sum_{i=1}^{4} \left(\frac{V_i}{V_{0i}} \right)^2}$$

Fig. 4.1.2-2: ADS27 Intrusion index normalization curves and required vibration velocity limits for helicopter occupants /19/



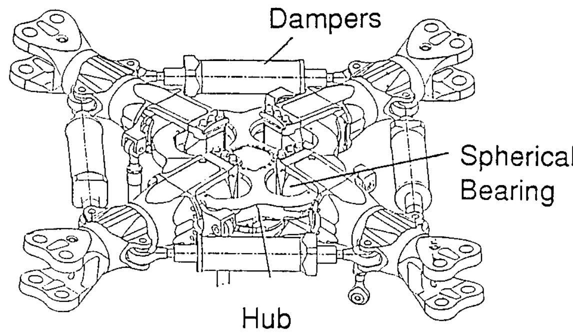
Equipment Location	Source Frequency F_i (Hz)	Peak Vibration Level L_i, at F_i in G	Value of W_2 and F_t
General (*)	5-25	0.5 + 0.1 * (F_i - 5)	W_2 = 0.002 F_t = 500
	25-40	2.5	
	40-50	2.5 - 0.1 * (F_i - 40)	
	50-500	1.5	
On Instrument Panel (*)			0.7 * General
External Stores (*)			1.5 * General
On or Near Drive	5-50	0.5 + 0.1 * (F_i - 5)	W_2 = 0.02
System Elements (**)	50-2000	5.0 + 0.01 * F_i	F_t = 2000

(*) $F_2 = 2 * F_1$, $F_3 = 3 * F_1$, $F_4 = 4 * F_1$. $F_1 = n_{blades}$/rev

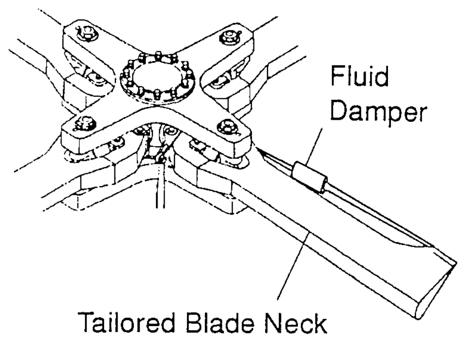
(**) $F_1 = F_4$ should be choosen based on drive train source frequencies

Fig. 4.1.3-1: MIL 810D, method 514.3, general spectrum and acceleration limits for equipment vibration qualification /20/

Hinged rotor with elastomeric bearings (system Spheriflex with interblade dampers, NH90)



Hingeless rotor with elastomeric pitch bearings (TIGER, ALH)



Bearingless rotor with flexbeam & torque tube for pitch control (EC135)

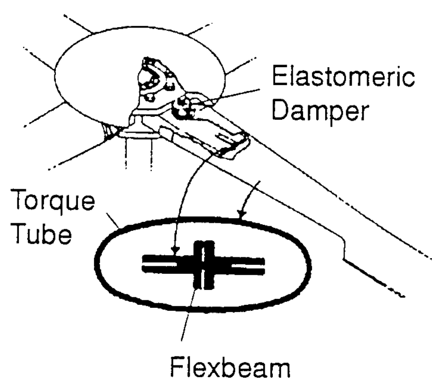


Fig. 4.2.1-1: Modern main rotor hub and centrifugal retention structural designs

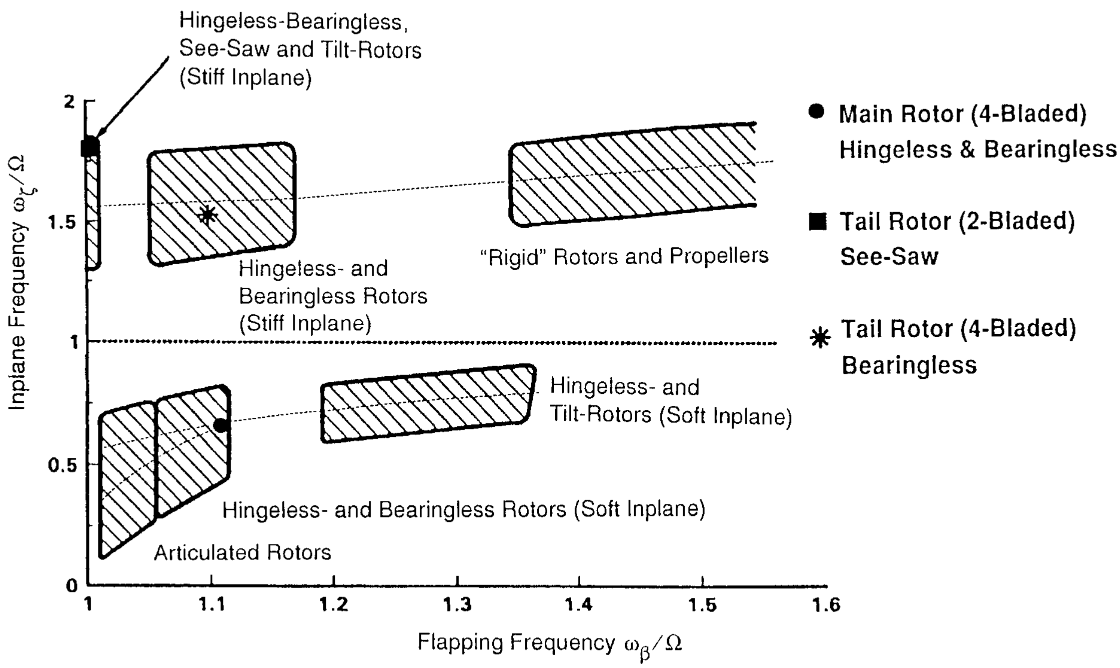


Fig. 4.2.1-2: Fundamental flap-lag frequency selection for rotors and propellors /22/

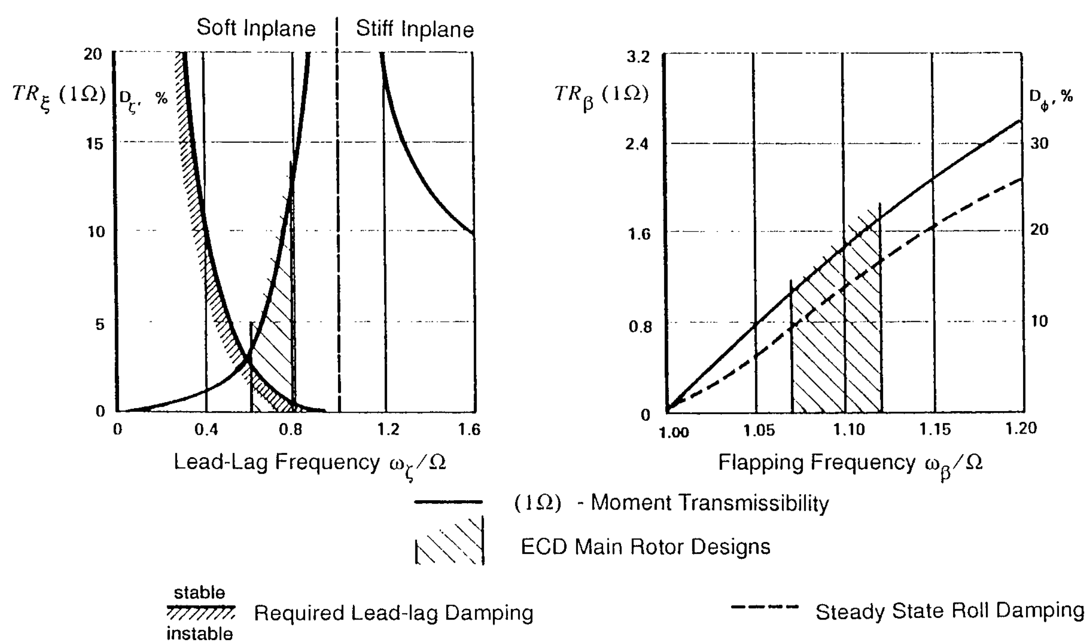


Fig. 4.2.1-3: Effect of blade lead-lag and flapping natural frequency placement on blade root moment amplification and damping /23/

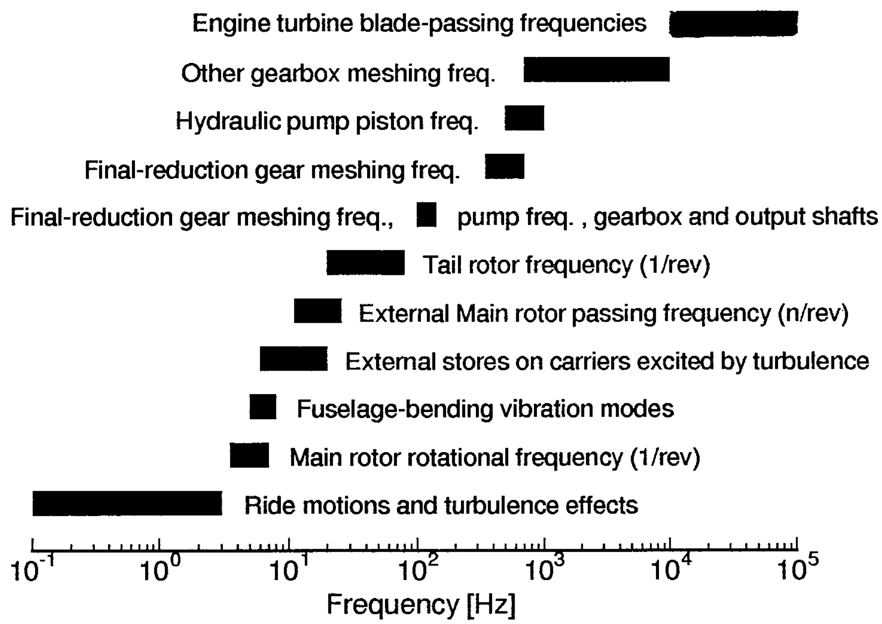


Fig. 4.2.2-1: Basic frequency schedule for helicopters

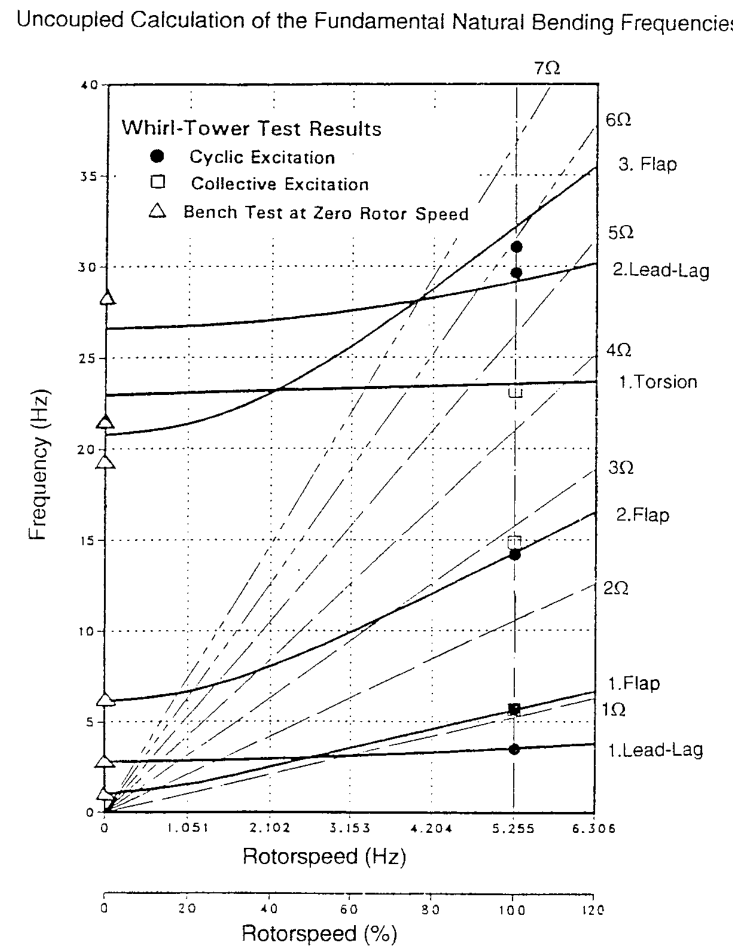


Fig. 4.2.2.-2: Main rotor frequency diagram TIGER

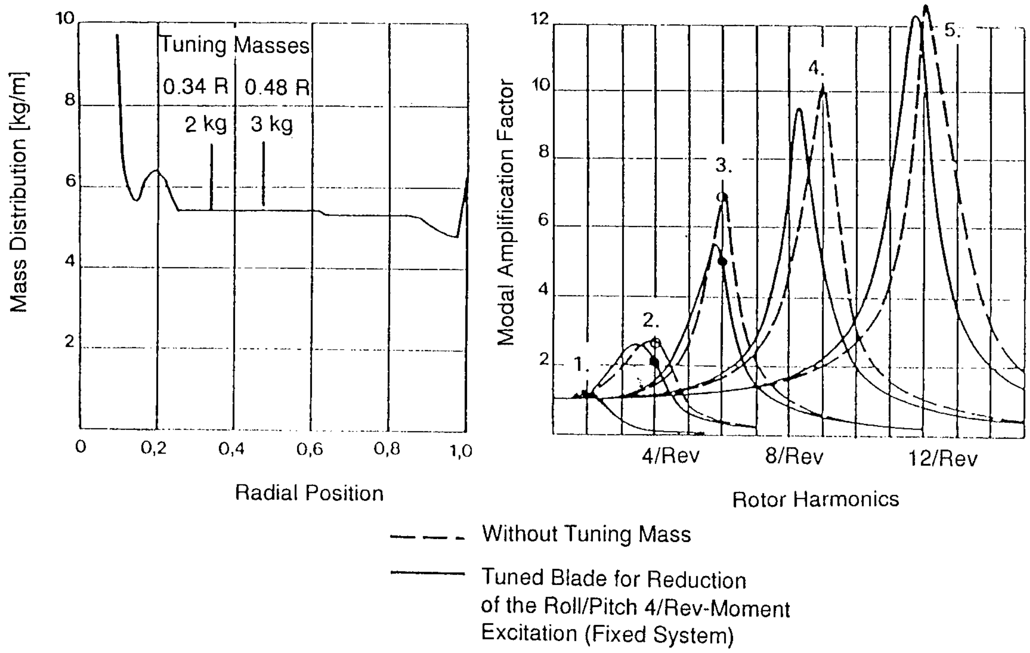


Fig. 4.2.2-3: Influence of tuning masses on the modal amplification factors for flap bending of the BK117 main rotor blade /23/

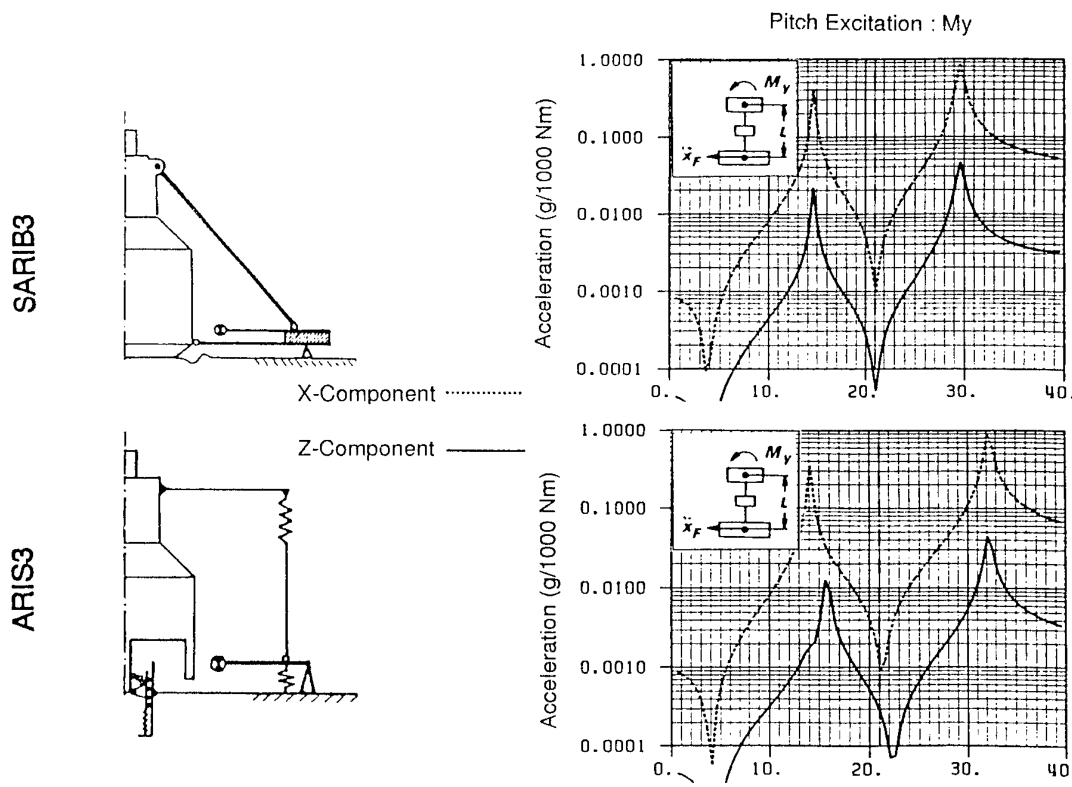


Fig. 4.2.2-4: Functional principle of SARIB and ARIS anti-resonance systems for vibration reduction /24/,/27/

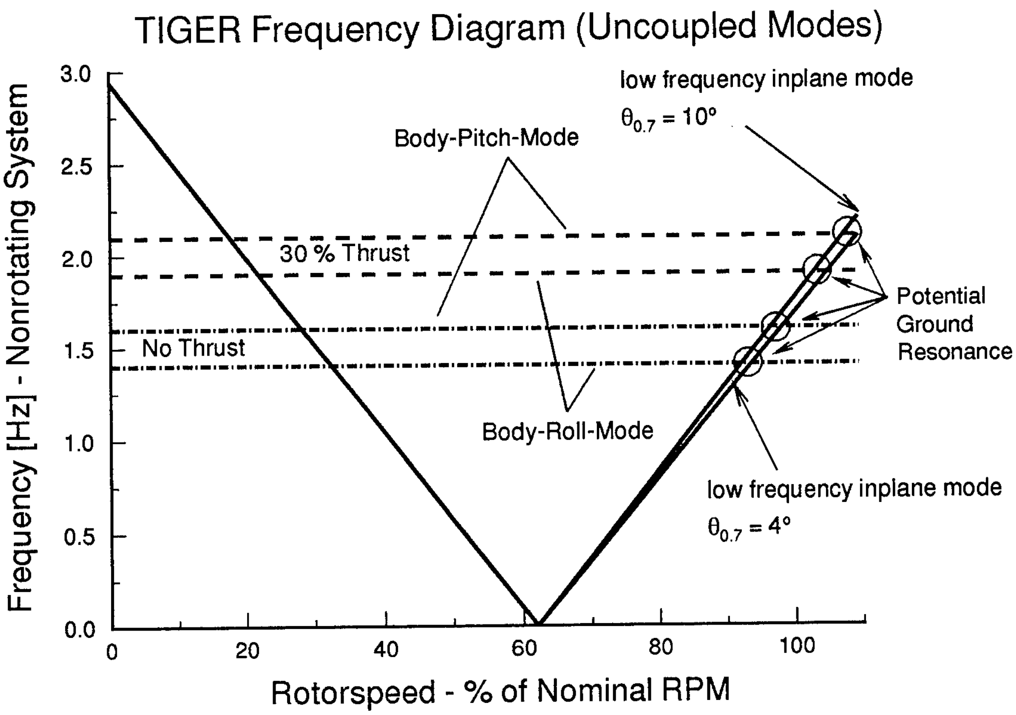


Fig. 4.2.2-5: Ground resonance frequency arrangement TIGER

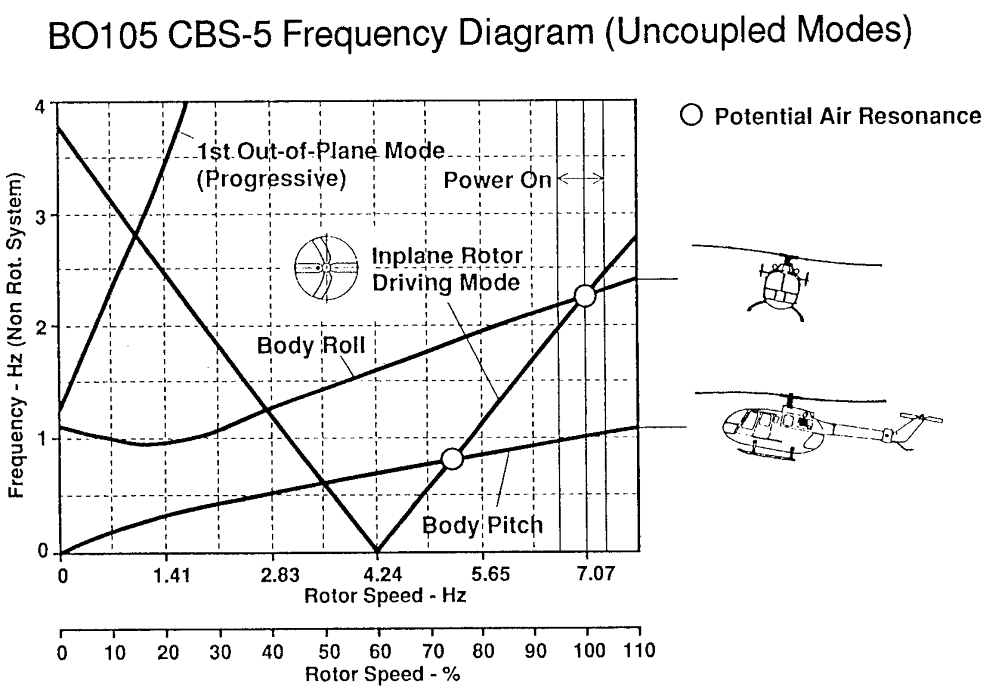
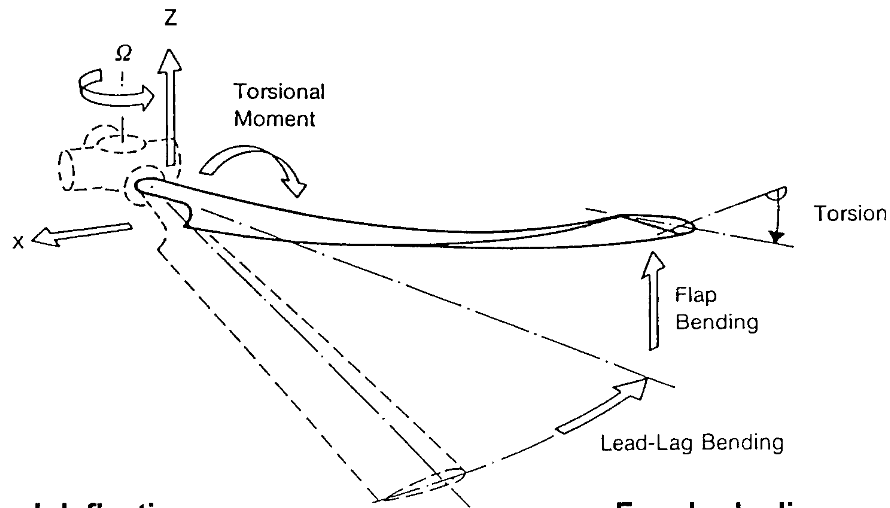
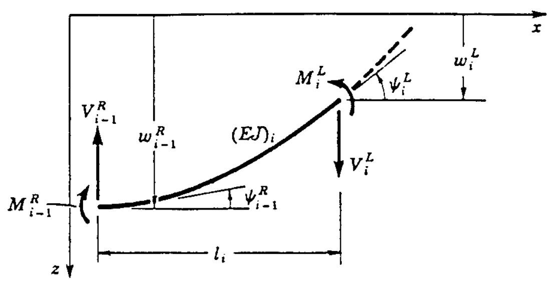


Fig. 4.2.2-6: Air resonance frequency arrangement BO105 /22/

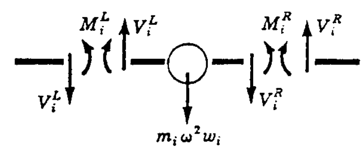
Blade degrees of freedom :



End forces and deflections for massless beam



Free-body diagram of mass m_i



Principle of transfer matrix method
Example: Beam bending without centrifugal force

(shear force V, moment M, slope ψ, deflection w, flexural stiffness EJ, length l, mass m, rotation velocity ω)

$$\begin{bmatrix} -w \\ \psi \\ M \\ V \end{bmatrix}_i^L = \begin{bmatrix} 1 & l & \frac{l^2}{2EJ} & \frac{l^3}{6EJ} \\ 0 & 1 & \frac{l}{EJ} & \frac{l^2}{2EJ} \\ 0 & 0 & 1 & l \\ 0 & 0 & 0 & 1 \end{bmatrix}_i \cdot \begin{bmatrix} -w \\ \psi \\ M \\ V \end{bmatrix}_{i-1}^R$$

$$\begin{bmatrix} -w \\ \psi \\ M \\ V \end{bmatrix}_i^R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ m\omega^2 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -w \\ \psi \\ M \\ V \end{bmatrix}_i^L$$

Double Beam BO 105, TIGER

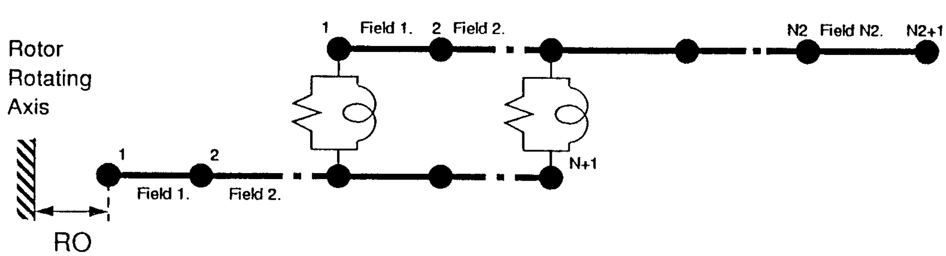
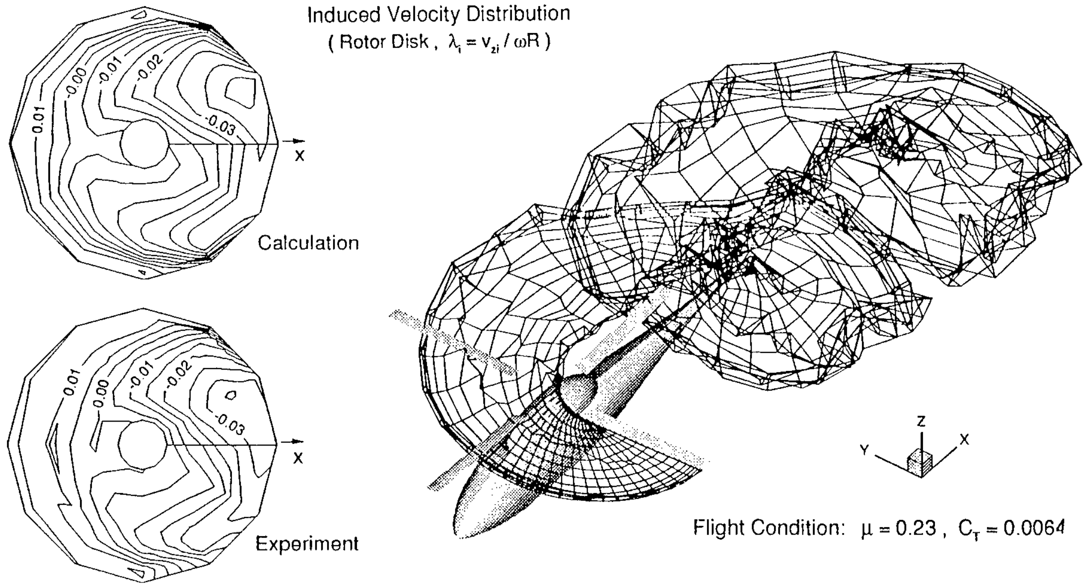
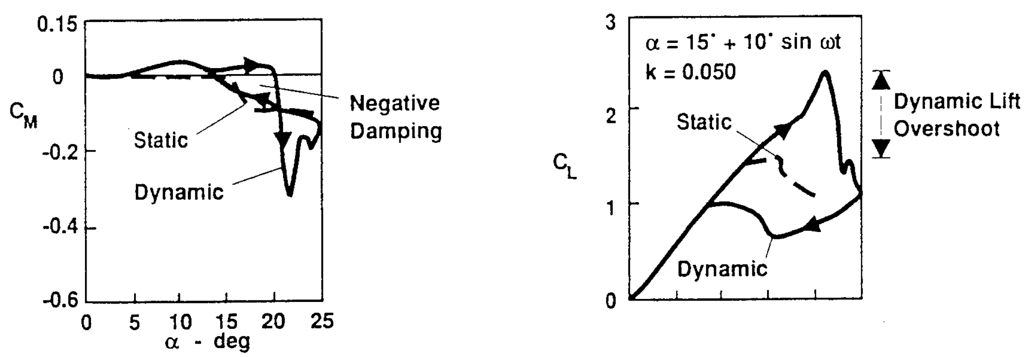


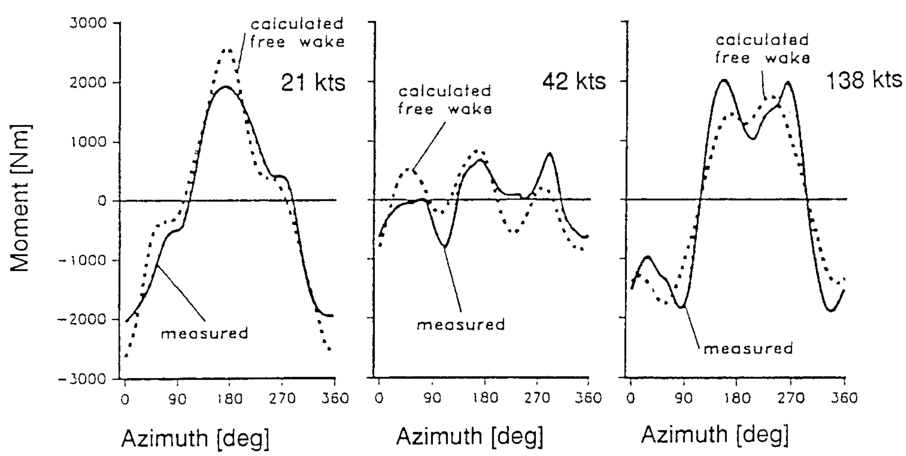
Fig. 4.3.1-1 : Transfer matrix method : Concept and application to the BO105 and TIGER main rotor /23/,/25/



Rotor free wake simulation and resulting inflow at the rotor disk



Dynamic stall effects in airfoil characteristics measurements



Prediction of rotor shaft bending moments by current aeroelastic tools
(EC135 at level flight)

Fig. 4.3.1-2: Aerodynamic excitation phenomena to be considered in modern rotorcraft computer codes /22/,/26/

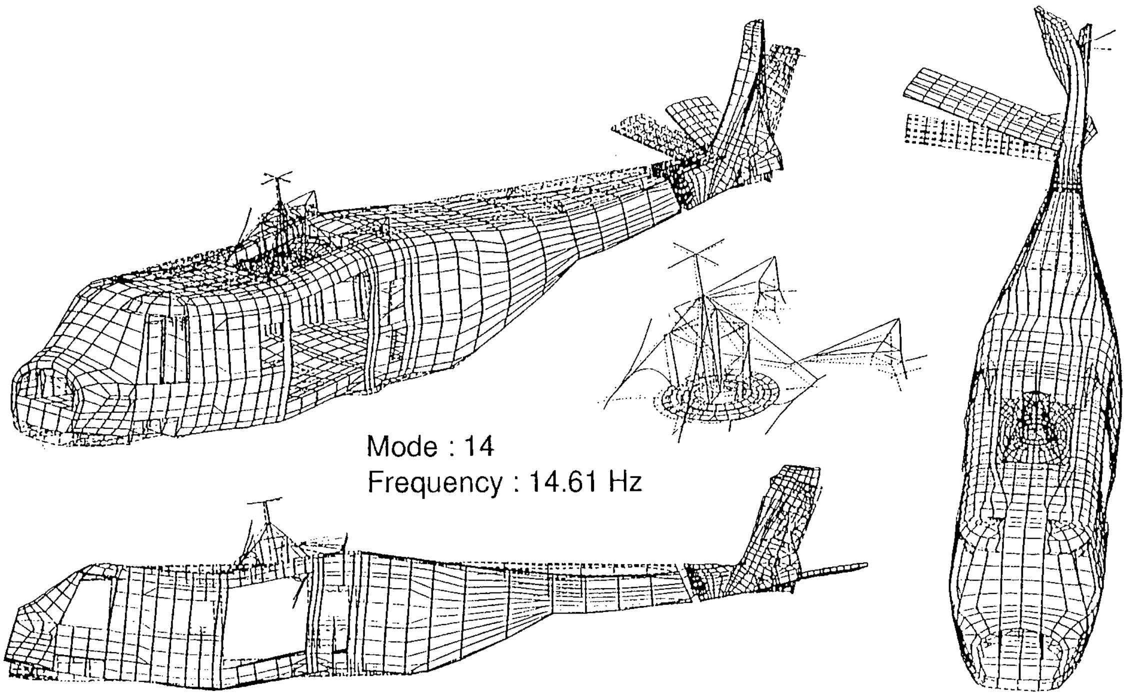


Fig. 4.3.2-1: NH90 fuselage mode shape at 14.6 Hz (predicted)

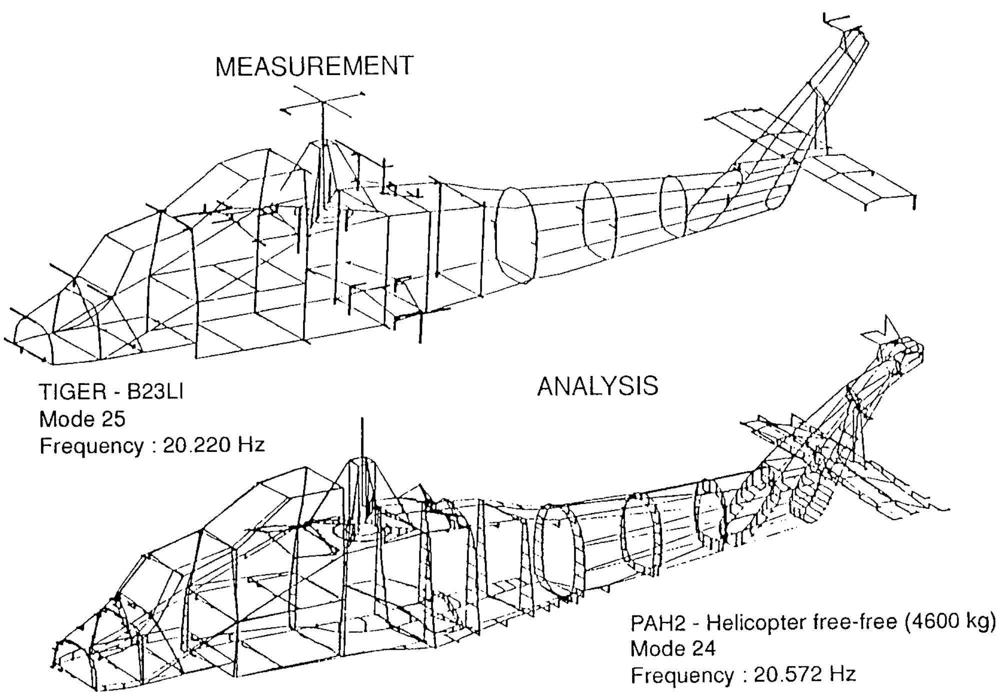


Fig. 4.4-1: Comparison of a calculated and measured TIGER fuselage mode shape at approx. 20 Hz

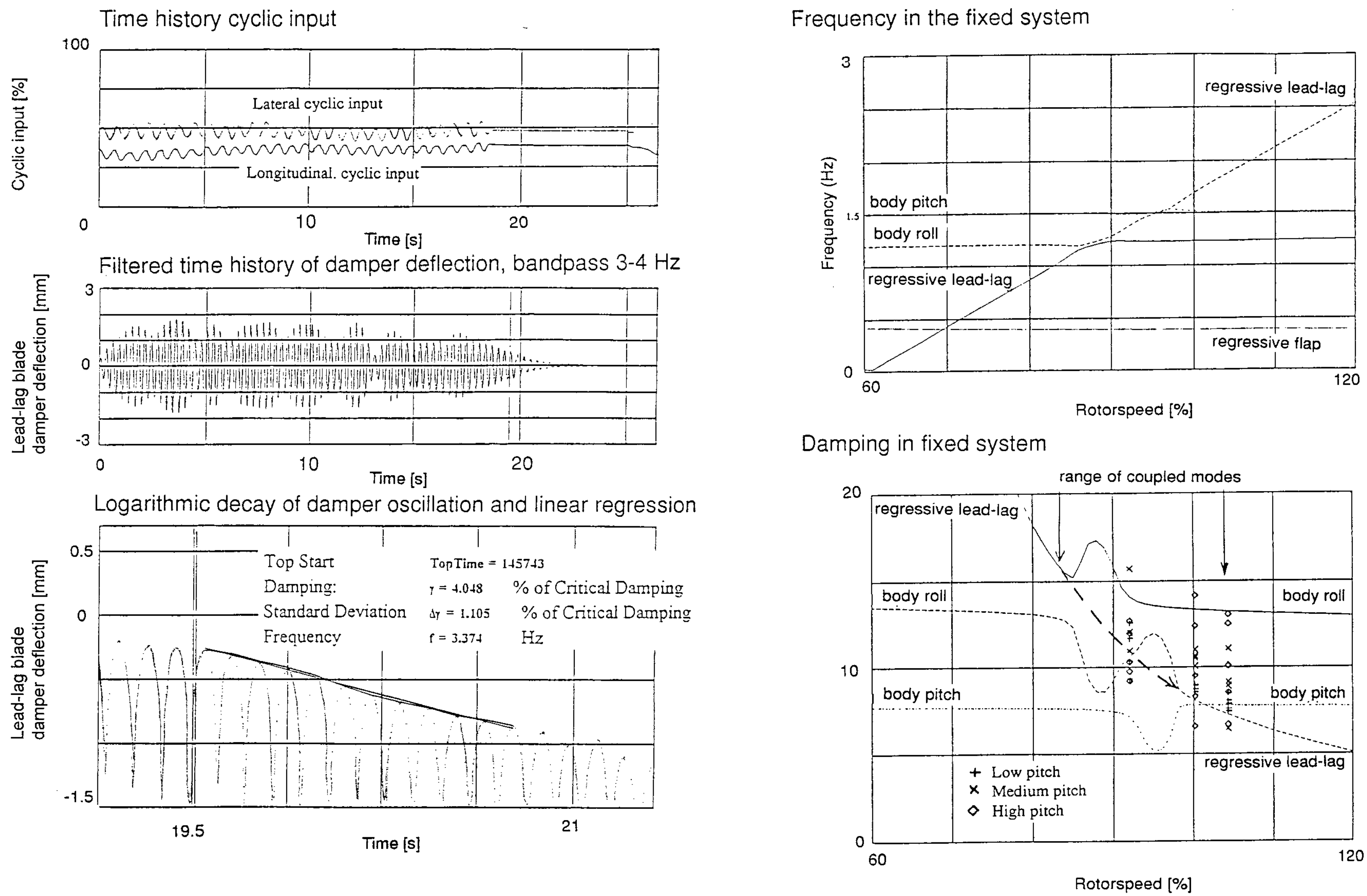


Fig. 4.4-2: TIGER - ground resonance test and damping results

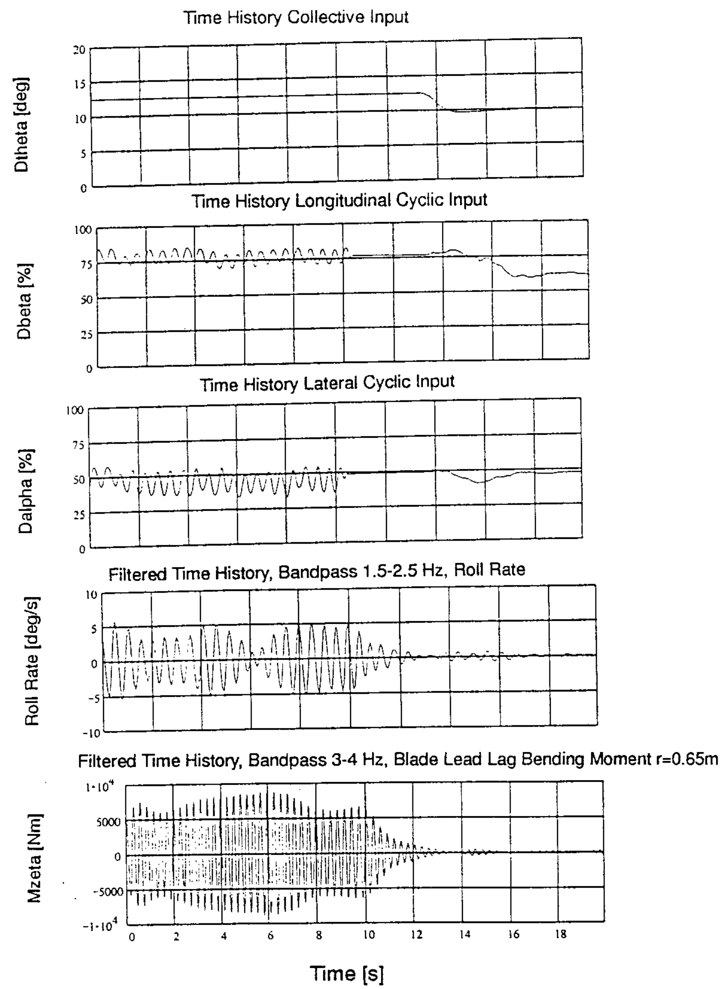


Fig. 4.4-3: Air resonance test TIGER

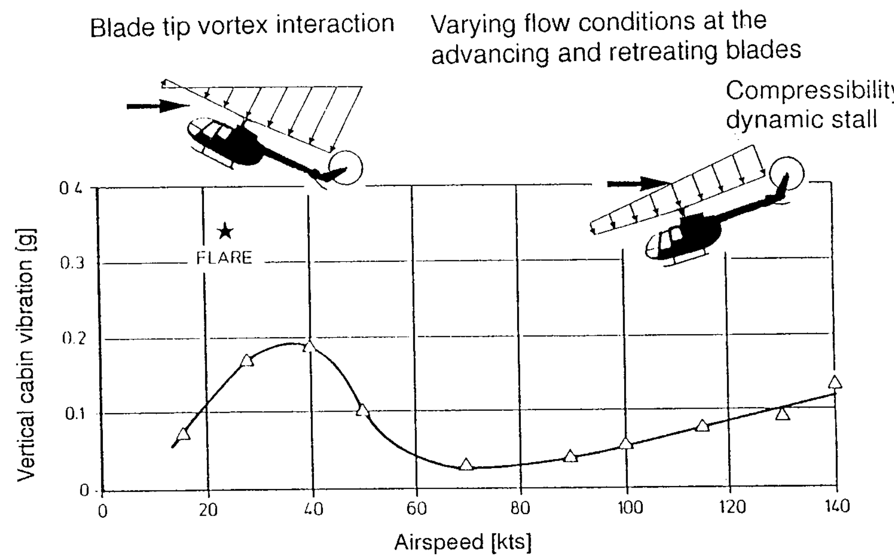


Fig. 4.4-4: Vertical cabin vibration (B0105 flight test) /24/

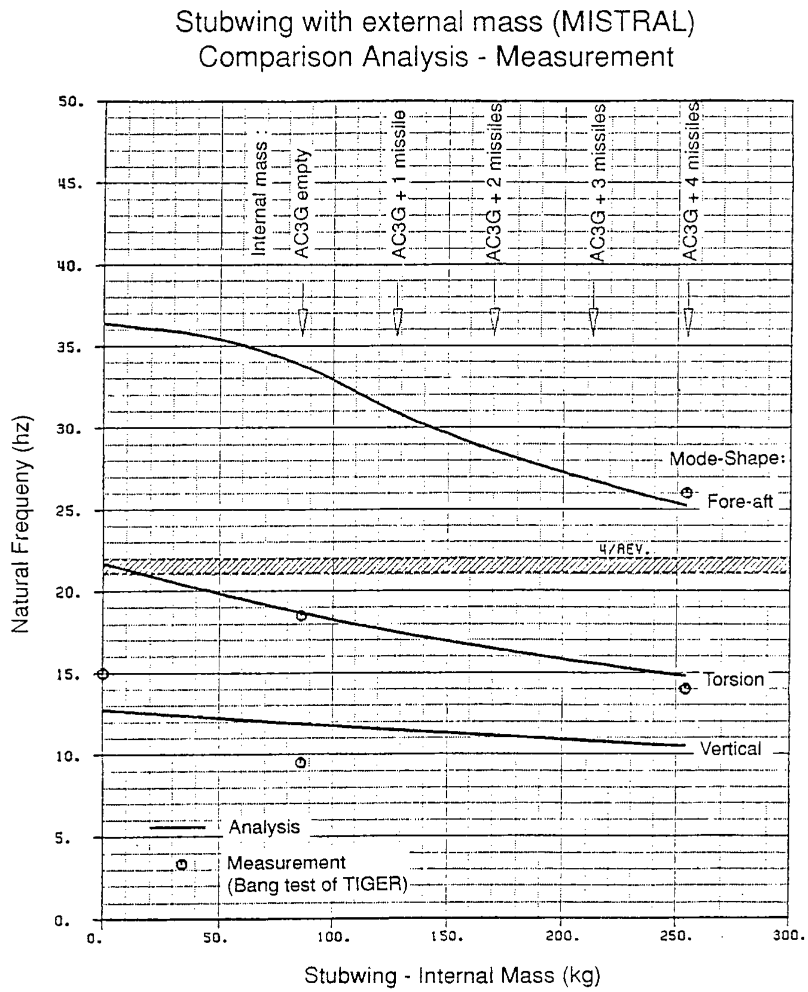


Fig. 4.5-1 : TIGER stubwing natural frequencies dependent of TRIGAT launcher loading configuration

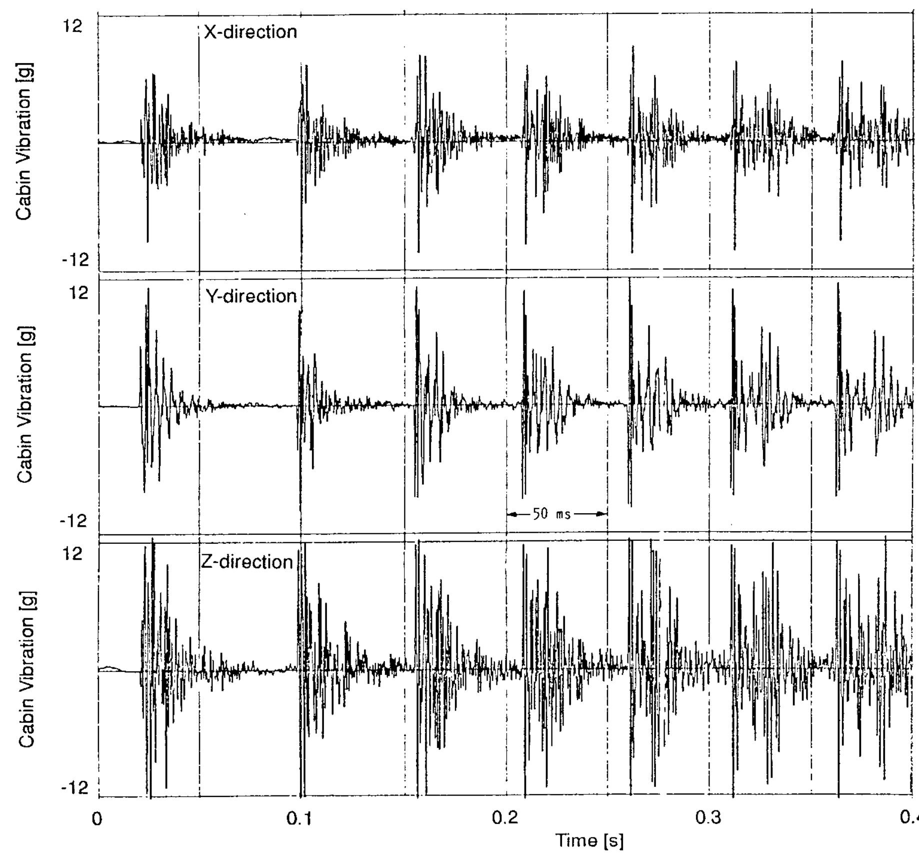


Fig. 4.5-2: Cabin vibrations due to machine gun firing, BO105 HMP (0.5") MG

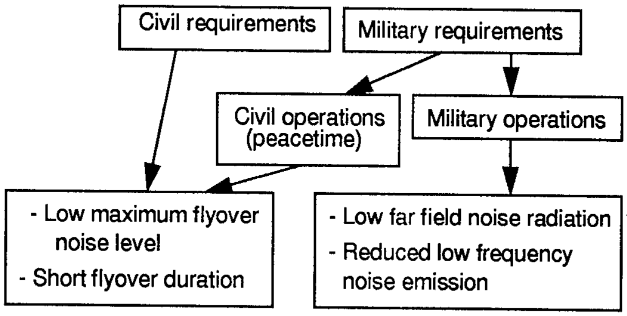


Fig. 5.1-1: Acoustic requirements for military and civil operations /33/

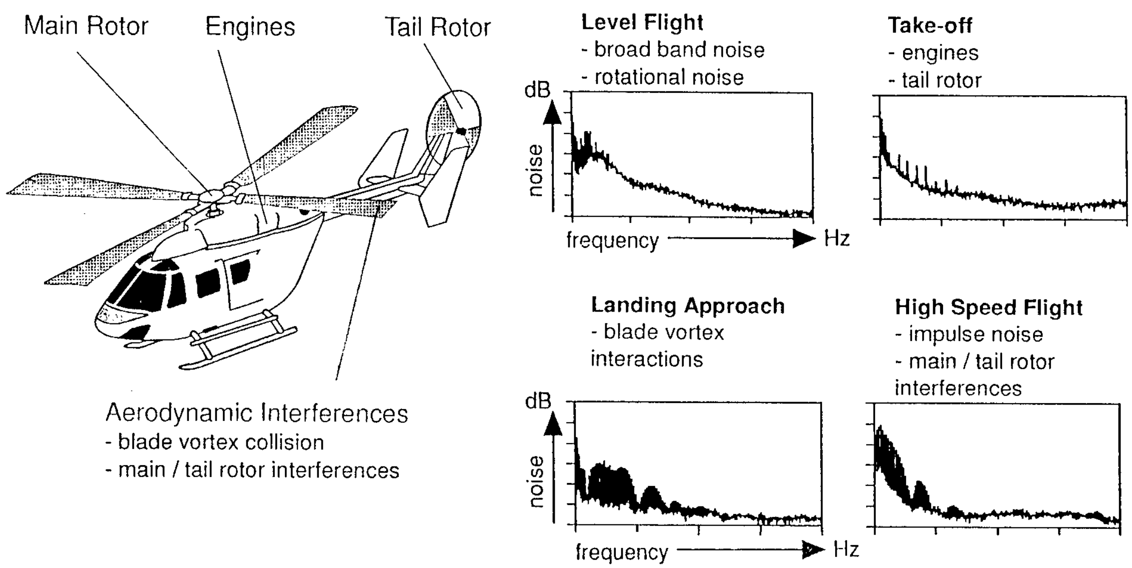


Fig. 5.2-1: Helicopter noise sources /34/

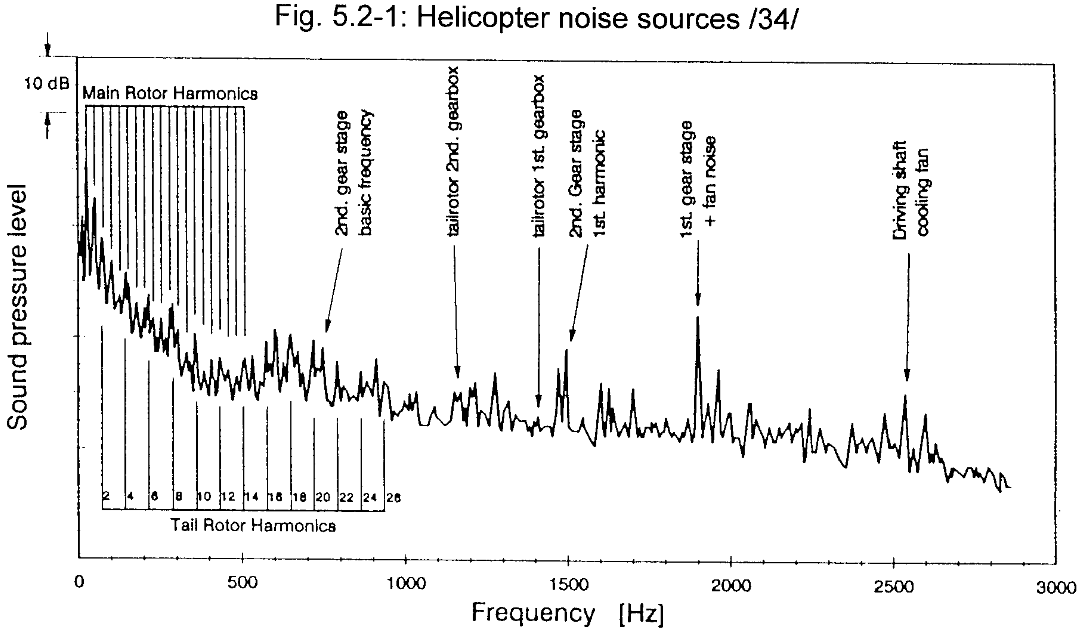


Fig. 5.2-2: Interior noise spectrum BK117

Influencing parameters on acoustic detectability:

- noise source characteristic
- air attenuation
- ground absorption (flight altitude)
- sensor characteristic
- masking noise at the observer position

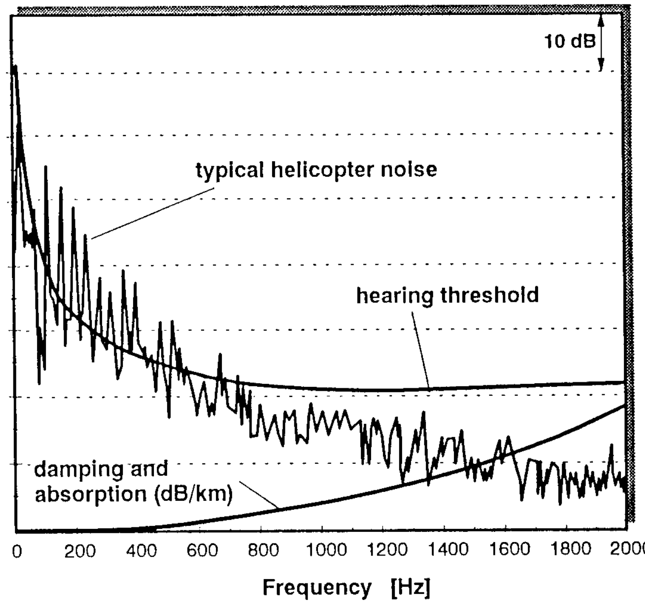


Fig. 5.3-1: Acoustic detectability of helicopters /33/

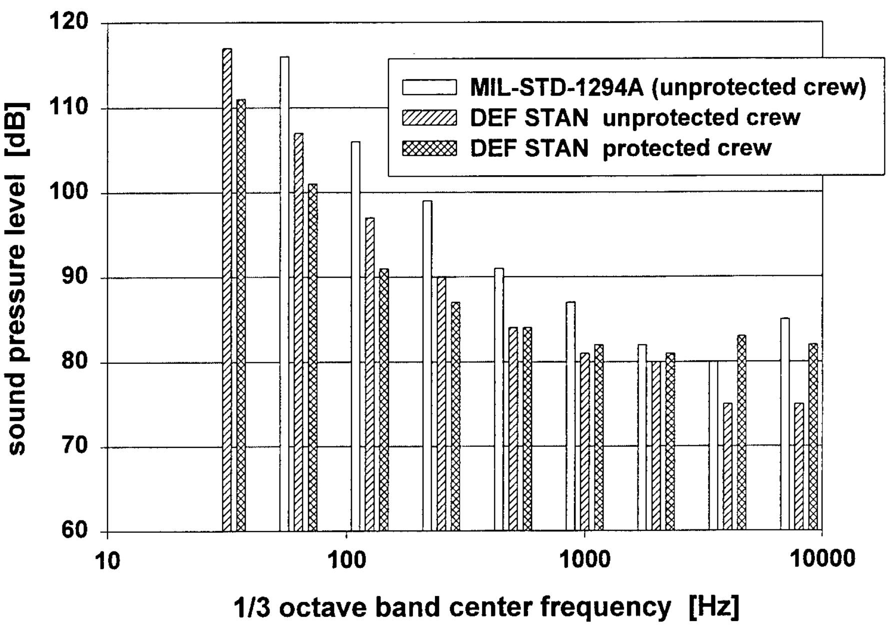


Fig. 5.4-1: MIL-STD 1294 + DEF-STAN 00-970Ch. 108 specification for interior noise /30/,/31/

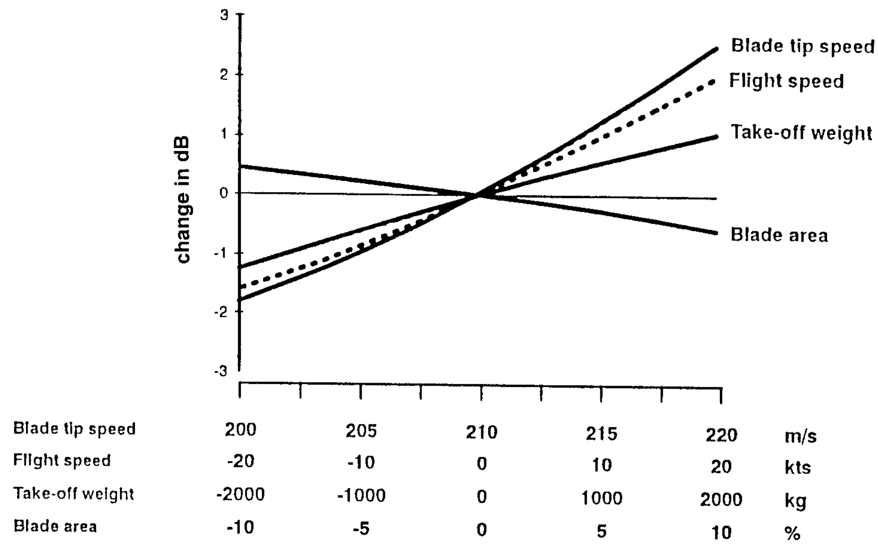


Fig. 5.5-1: Effect of different design parameters on helicopter exterior noise

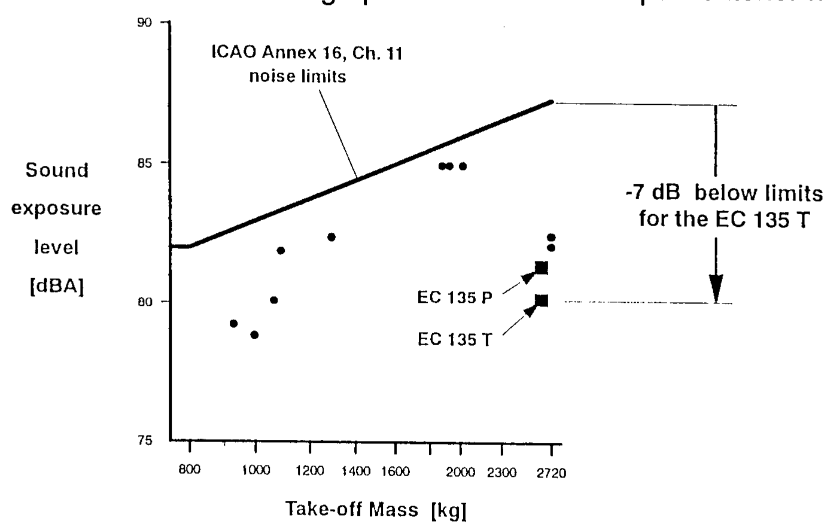


Fig. 5.5-2: Noise certification measurements EC135 vs. ICAO noise limits

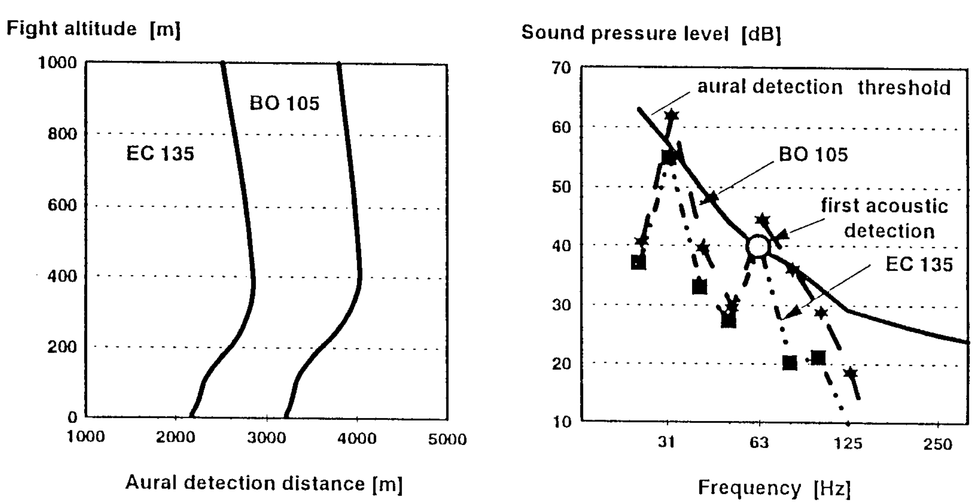


Fig. 5.5-3: Improvement of aural detectability /33/

The AH-64D Apache Longbow Weapons System

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1. ABSTRACT

The AH-64D Apache Longbow represents a significant enhancement in the evolution of attack helicopters. It is a fourth-generation precision weapon system that is totally integrated. The high level of integration provides an efficient and operationally effective system and gives commanders at all levels the ability to meet modern battlefield requirements ranging from peacekeeping to major regional conflict. This paper examines some of the AH-64D Apache Longbow capabilities, its inherent design features that maximize performance and provides a summary of the demonstrated level of performance.

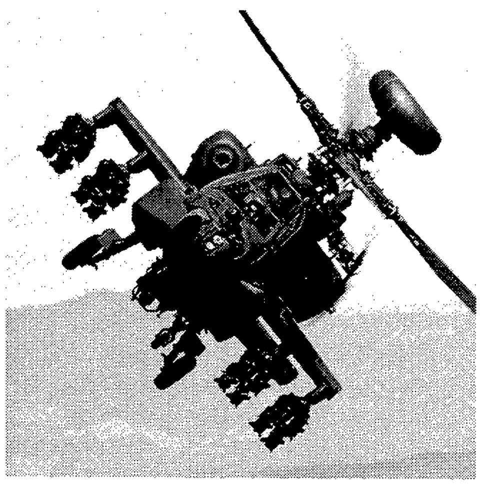

Figure 1. AH-64D Apache Longbow

2. INTRODUCTION

No longer can helicopters be viewed as platforms for carrying weapons. Rather, modern attack helicopters must be viewed as total weapon systems in which external ordnance is considered an integral part of the system. The Apache is not just an aerial weapons platform to which modified infantry weapons are bolted. That definition is more representative of the late 50's and the early 60's first-generation attack helicopter.

The Apache is not a rotary-winged air vehicle to which guns and rockets are tailored for aerial flight independent of the avionics, and attached as an afterthought. This describes the late 60's and 70's second-generation attack helicopter in which the airframe was designed in whole or in part for other operational requirements.

The AH-64A Apache is a fully integrated, highly dense, lethal weapon system, designed exclusively, and finely tuned and tailored, for operations at night. It is a third-generation attack helicopter. But, the AH-64D Apache Longbow brings a totally new dimension to attack helicopters. The Longbow fire control radar (FCR), digital communications, expanded situational awareness, precise navigation, the RF Hellfire missile and other improvements give it a robust, expanded capability to perform a wide range of operational requirements. It is the only fourth-generation attack helicopter available in the world today.

The AH-64D Apache Longbow is the most versatile, combat effective helicopter in the world. The modernized Apache and the revolutionary Longbow weapon system provides the warfighting capability to operate effectively and survive in the 21st century and the flexibility to contend with modern operational requirements. The AH-64D Longbow is the most lethal and survivable attack helicopter available in the world.

3. APACHE LONGBOW SYSTEM ENHANCEMENTS

The Apache Longbow represents a significant improvement to the combat-proven AH-64A. The most distinguishing external characteristic of the Apache Longbow is the mast mounted assembly (MMA) which houses the FCR and is mounted on top of the rotor system. Internally, the AH-64D is totally new. The FCR, coupled with the advanced crewstation, a significantly improved navigation and communication system and an integrated digital information system provides the first lethal U.S. Army system of the information age.

Let there be no mistake, the Apache Longbow was designed to operate and survive in high intensity conflict and destroy large concentrations of mechanized and armored forces. This capability has been demonstrated and more than exceeded the Army's expectations. However, the ability to digitally communicate battlefield information, collected by the FCR and other sensors, in near-real-time, over any of the onboard tactical radios, makes the Apache Longbow both a lethal maneuver element and intelligence asset. Its capabilities can be used for intelligence, targeting for the force, attack coordination, and when necessary, destroying the enemy. The greatly enhanced situational awareness provided by the FCR and the digital communication capability make the AH-64D the weapon of choice on the modern battlefield.

Figure 2 illustrates the major system enhancements incorporated in the AH-64D and include:

a. The MANPRINT crewstation uses large multi-purpose displays (MPDs) for enhanced situational awareness. Systems management is automated allowing the crew to spend more time on mission management. Full capability to fly and fight exists in both cockpits.
b. The digital communication capability utilizes tri-service compatible, secure, anti-jam radios and a high capacity improved data modem (IDM).

Paper presented at the AGARD FVP Lecture Series on "Helicopter/Weapon System Integration", held in Winchester, UK, 19-20 May 1997; Athens, Greece, 22-23 May 1997, and published in LS-209.

c. An advanced avionics architecture with dual MIL-STD-1553B muxbuses and redundant processing centers for greater mission reliability.
d. An improved navigation capability with dual embedded global positioning inertial (EGI) navigation units for precise battlefield maneuverability, precision targeting, and digital data communications.
e. -701C Engines for improved high, hot performance
f. Expanded Forward Avionics Bays with increased electrical power and new vapor cycle cooling system for better maintainability and avionics reliability.

The former Chief of Staff of the US Army, General Gordon Sullivan, put the AH-64D in perspective at the prototype Apache Longbow rollout ceremony in September 1993 when he said: "What this great helicopter represents is teamwork. The people, the politicians, the uniformed members of the services coming together to produce a weapon system that represents information age warfare. It transcends what it really is. It is a helicopter, but it begins processing information so quickly that the Army is now able to capture the battlefield in all of its dimensions: speed, space and time. We know where we are! We know where you are! We know where you are not! And we are coming after you day and night until we win. That's what this helicopter is all about—Teamwork, and information-age warfare."

This is a thought-provoking statement of fact and a powerful message. The bottom line is that the AH-64D Apache Longbow is a total success story. It is designed around the pilots and logisticians who will crew and support it, the commanders and the soldiers who will rely on it, the drivetrain and fuselage which give it strength, the avionics which give it intellect, the weapons which give it muscle, the air foils which propel it effortlessly with grace, dignity, superiority and abandon. All are exactly tailored, finely tuned, and precisely packaged into the finest attack helicopter capability in the world today.

4. THE SYSTEM

The Apache Longbow weapon system is totally integrated with incredible new combat capabilities. The FCR, coupled with the RF Hellfire missile and the integrated Apache weapon system, provide an unprecedented, automatic, multi-target acquisition and precision engagement capability. Figures 3 through 6 illustrate the major components of the Apache Longbow weapon system.

The millimeter-wave FCR mounted above the main rotor and the fire-and-forget Longbow Hellfire modular missile system (LBHMMS) were developed to overcome mission deficiencies associated with currently fielded electro-optical weapon systems. The application of millimeter-wave radar technology provides significantly improved combat capability in adverse weather and battlefield obscurants and a major reduction in helicopter exposure times for target acquisition and weapon delivery.

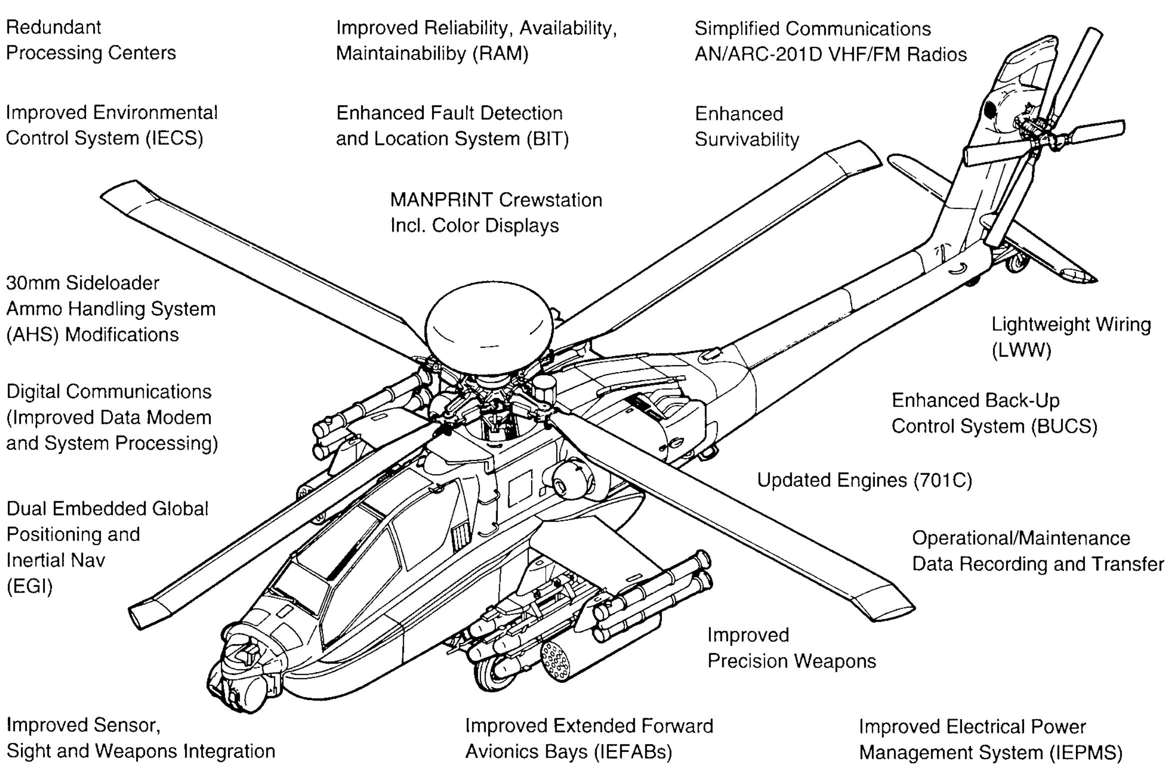

Figure 2. AH-64D System Enhancement

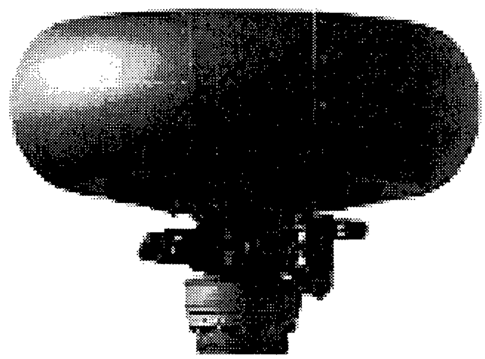

Figure 3. Longbow fire control radar and radar frequency interferometer

Mounted underneath the FCR, the radar frequency interferometer (RFI) provides a long-range passive identification capability which is essentially for timely threat avoidance or engagement.

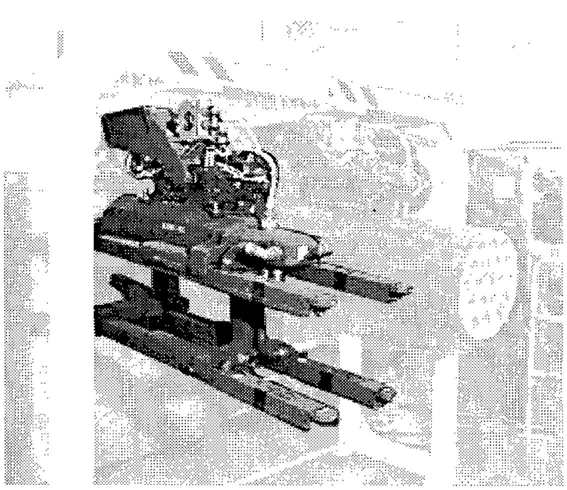

Figure 4. M299 launcher

The Hellfire missile system includes the M299 Launcher and the AGM-114L Longbow Hellfire missile. The launcher is compatible with both laser and radar (RF) Hellfire missiles and all previous versions of the laser Hellfire. The AGM-114L is the latest addition to the Hellfire family. It is composed of the Hellfire II missile equipped with a millimeter-wave missile seeker. This combination provides the fire-and-forget capability after a target has been assigned to the missile by the weapon system.

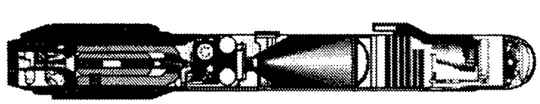

Figure 5. AGM114L Hellfire II missile

The AH-64D platform is the host for the Longbow system and enables the effective integration of this new capability. It incorporates a modernized, totally integrated crewstation incorporating significant systems automation that enable the crew to concentrate on the mission, not manage the aircraft. Other aircraft improvements include precise navigation, long range digital communications, increased readiness through improved reliability, enhanced fault isolation, onboard maintenance data recorder (MDR) and an interactive electronic technical manual (IETM) for better maintainability.

Figure 6. The Apache Longbow

Earlier this year the Air Force Acquisition Executive, Mr. Art Money, upon returning from a Longbow night flight commented on the integrated nature of the Apache Longbow when he said, "this aircraft has better weapons integration and pilot cueing than the F-117 and is what we are looking for in the F-22."

5. FLEXIBLE TARGETING

The FCR provides a very flexible, very rapid, broad area, multi-target acquisition capability and enables the Apache Longbow to rapidly collect real-time battlefield information. For example, in the wide scan, ground targeting mode, over 50 square kilometers are searched in seconds. Militarily significant targets are detected, classified, prioritized and displayed to the crew. This information can be digitally transmitted to other AH-64Ds or a host of other digital receivers and is unaffected by adverse weather or battlefield obstructions. The low sidelong antenna design and the low probability of intercept (LPI) radar waveforms make it difficult to detect FCR emissions and minimize the susceptibility to electronic countermeasures. Figures 7 through 11 provide pictorials of the various targeting modes discussed below.

The FCR provides two operational modes (ground targeting mode (GTM) and air targeting mode (ATM)) for targeting and a terrain profile mode (TPM) to aid pilotage and navigation in the adverse weather or obscured environment. The RFI operates in each mode or can be operated independently. The use of the RFI and FCR data collectively provides an inherent suppression of enemy air defense (SEAD) capability.

5.1 Ground Targeting Mode

The GTM is the primary target acquisition and weapon delivery mode. It provides 4 selectable sector searches, 90°, 45°, 30°, and 15°, and each sector is positionable up to 90° from the AH-64D centerline. The FCR will search, detect, locate, classify and prioritize moving and stationary ground targets, hovering or flying helicopters and low flying fixed-wing aircraft. The ground targets are classified as tracked vehicles, wheeled

vehicles or air defense systems. Within seconds after unmasking the MMA and initiating the GTM scan, the crew is presented with up to 128 classified targets on the tactical situation display (TSD) and the 16 highest priority targets are presented for engagement on the FCR targeting display. Target prioritization is selectable based on mission, target classification, target state, and other variables. The crew can immediately commence firing once targeting data is displayed.

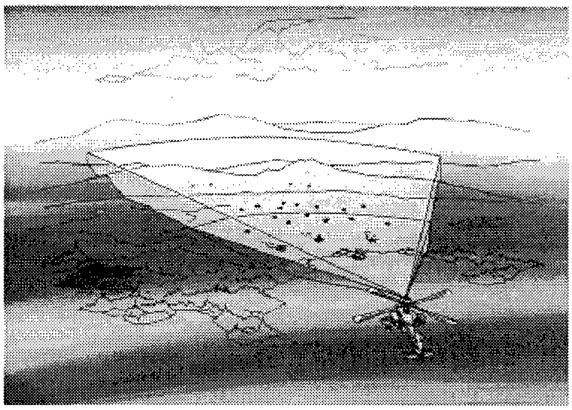

Figure 4. Ground targeting mode

The GTM scan utilizes two distinct radar waveforms which are interleaved to minimize the target acquisition timeline. Stationary ground targets in clutter are detected and classified using a frequency agile, polarization diverse waveform. The stationary target detection and classification signal processing algorithms represent a technology breakthrough that gives the Longbow FCR a unique capability. False alarms from clutter and other man-made objects have been reduced to a very low rate which does not diminish system effectiveness. Moving ground targets and airborne targets are detected and classified using a pulse Doppler waveform which provides a high detection probability and a very low false alarm rate. This combined capability provides a unique degree of effectiveness regardless of the target state.

5.2 Air Targeting Mode

The ATM provides an air threat warning and self-defense capability unique to the AH-64D Apache Longbow. ATM has a continuous 360° search capability with a maximum range of 8 km. It detects, locates, classifies and prioritizes hovering and flying helicopters and fixed-wing aircraft. Moving ground targets are rejected. The crew can select reduced scan sectors of 180° or 90° and a single scan if mission requirements dictate.

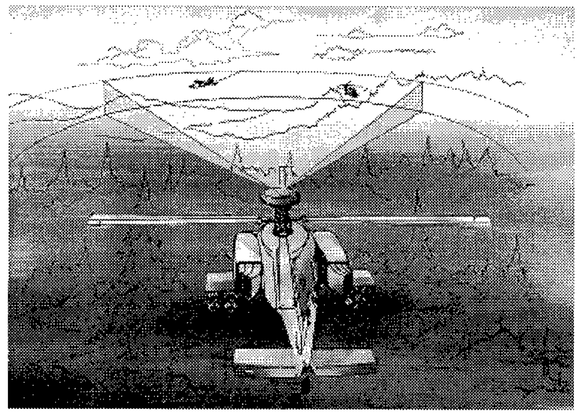

Figure 8. Air targeting mode

The ATM uses a pulse Doppler waveform for the detection and classification of helicopters and fixed-wing aircraft. This provides the ability to detect airborne targets in clutter with a high probability and very low false alarm rate. Targeting data can be used for handover to a Longbow missile against helicopter targets or for cueing of an air-to-air missile. With one or two team members using ATM for air overwatch airborne threats can be attacked or avoided.

5.3 RF Interferometer

The AN/APR-48A RFI gives 360-degree threat warning and identification and fine direction finding over a 90 degree sector centered on the FCR line-of-sight. The interferometer antenna array is boresighted with the FCR antenna so RFI detects can be merged accurately with FCR targets. Threat characteristics for over 100 radar emitters can be programmed in the removable User Data Module and this identification library can be updated easily to accommodate new threats. Unique search, track and guidance signatures are identified to aid in target prioritization.

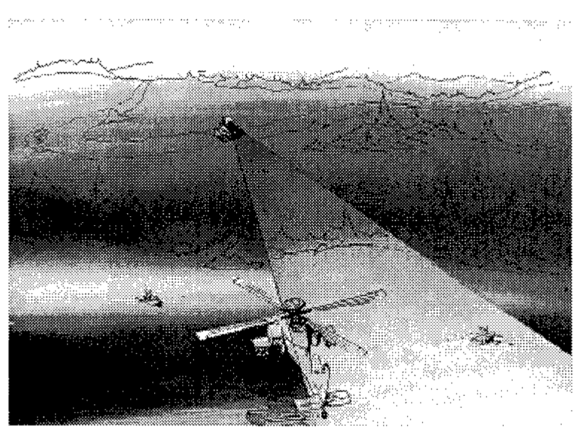

Figure 9. Radio frequency interferometry

5.4 Suppression of Enemy Air Defense (SEAD)

The Apache Longbow has the inherent capability to suppress enemy air defense systems (SEAD) and engage hostile forces from standoff range. The RFI is operational in each mode to provide immediate threat warning. The RFI has been integrated with the other weapon system components to provide a deadly

combination for the rapid detection, identification and destruction of hostile air defense systems. The suppression of enemy air defenses is critical to survivability and the passive mast-mounted RFI system with its detection sensitivity and direction finding capabilities give the advantage to Apache Longbow.

An FCR cued search acquisition process has been automated to minimize response time in combat situations where an air defense system becomes active. When the RFI detects an emitter, the pilot or copilot/gunner initiates a *cued search.* With a single button push, the FCR performs an immediate narrow scan of the emitter azimuth, "merges" the most likely target or targets, and automatically computes a fire control solution. Almost simultaneously, target symbology is presented to the crew and RF missiles are armed for immediate launch. All the pilot needs to do is pull the trigger and mask the helicopter as the fire-and-forget RF Hellfire missiles fly to and destroy the designated targets.

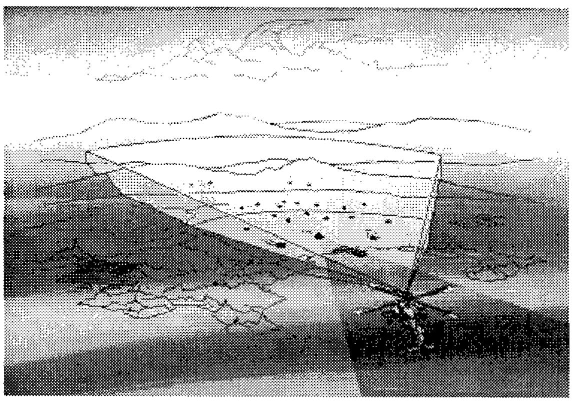

Figure 10. Suppression of enemy air defenses

This automated engagement and attack sequence provides the crew a number of options: effectively avoid contact, accurately (digitally) report ADA locations, suppress the target through digital fire support requests, or rapidly engage and destroy the threat autonomously. This automated process gives the Apache Longbow the inherent air defense suppression capability and the decisive edge when seconds count.

5.5 Terrain Profile Mode

The FCR terrain profile mode (TPM) provides an aid to navigation during nap-of-the-earth flight with reduced visibility. TPM measures the elevation angle to terrain out to a range of 2.5 km and provides terrain avoidance information that the pilot can use to select routes with best masking. The radar data supplements the pilot night vision system (PNVS) FLIR display when adverse weather limits the look-ahead range. TPM continuously scans a forward sector whose width is determined automatically by airspeed, a 90° sector for airspeeds greater than 50 knots and a 180° sector for slower speeds.

TPM also provides an obstacle warning to alert the pilot to navigation hazards. The FCR's signal processing and classification capability is utilized to detect tall man-made objects like towers and generate obstacle warning symbols for display at the appropriate range.

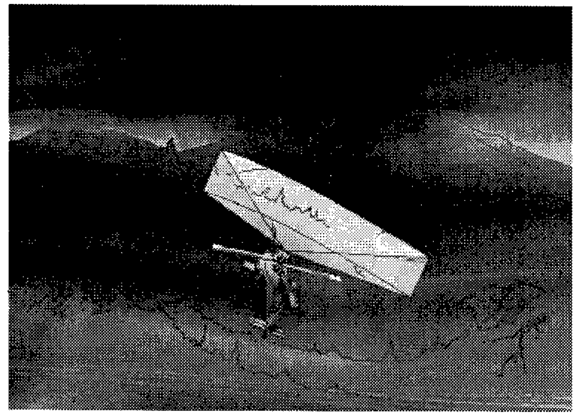

Figure 11. Terrain profiling

TPM has two display formats which can be selected simultaneously if the pilot desires. Terrain profiles, which show the elevation angle at a fixed range, can be superimposed on PNVS video. Up to 4 profiles can be displayed, along with obstacle warnings, on the 40° field-of-view IHADSS helmet sight. Stored terrain profile data is used to update the display as the pilot rapidly slews his head. A head-down display is also available where terrain elevation information is presented in a range-angle format on the MPD. Clearance planes are set at the AH-64D altitude and at a selected terrain clearance; the display then depicts terrain which exceeds these elevation planes.

Combining the PNVS FLIR imagery and radar terrain mapping data provides the flight crew with increased obscurant and adverse weather penetration capabilities for both terrain and obstacle avoidance. Apache Longbow can get to and from the fight in weather that keeps other aircraft on the ground.

6. MANPRINT CREWSTATION FOR EFFICIENT AND EFFECTIVE OPERATIONS

The crewstation contributes significantly to the mission success of the Apache Longbow. Figures 12 and 13 are photos of the Apache Longbow crewstations. The large MPDs provide the situational picture in easily understandable visual formats. The system allows the crew to access any information with minimum (3-5) steps and display the information on any one of the four MPDs. Not only can preplanned operational graphics (boundaries, separation zones, neutral zones, authorized operation areas, cultural features) be displayed, but they can be displayed in geographical relation to the aircraft's sensor information. Either crew member can operate all systems but normally the pilot flies the Apache, from the back seat, and the copilot/gunner operates the mission equipment.

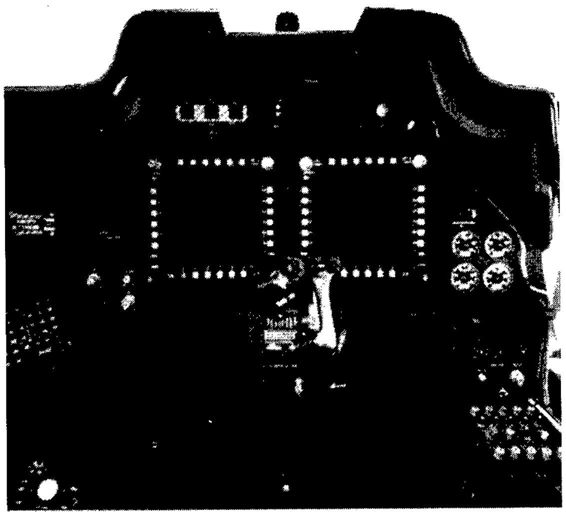

Figure 12. Pilot's MANPRINT crewstation

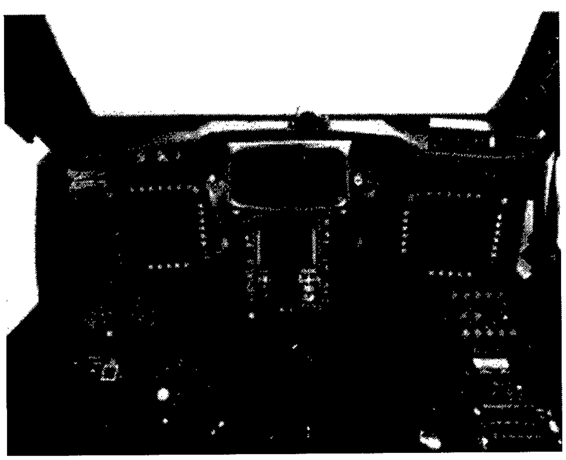

Figure 13. Copilot MANPRINT crewstation

7. SEE THE BATTLEFIELD

The Apache Longbow has the ability to "see" broad areas of the battlefield and provide that information to commanders in near-real-time. The FCR, precision navigation, and the simple, efficient MANPRINT crewstation, enable Apache Longbows to provide the commander essential battlefield information during day, night, adverse weather and obscured conditions. The improved communications systems can link digitally with a host of other platforms and systems in the area of operations. These enhancements significantly improve not only the quality of situational updates but enhance the responsiveness and proactive capability of the force. The ability to see the battlefield and communicate what you see is a major factor in the Apache Longbow's capability to protect our forces.

Figure 14 provides a representation of the displays and information typically displayed to each crewmember. The MPDs provide the medium to communicate the preplanned and real-time information to the crew. The left display shows the results of a FCR scan in the GTM with the highest prioritized targets displayed. The top priority targets are represented by symbology on the FCR display. The target symbols indicate the target's classification and whether it is stationary or moving. The highest priority target is indicated by the diamond symbol. The crew can engage this target simply by activating the weapons system and pulling the trigger or they may select a different target within the priority list. The right display is the tactical situation display (TSD). On the TSD, all detected targets are displayed, along with the FCR footprint indicating the area covered, in relation to the preplanned operational graphics and control measures. Crewmembers have the option to tailor the information displayed to the phase of the mission or their individual preferences.

The sight subsystem also includes the target acquisition and designation sight (TADS) which has forward looking infrared (FLIR) and TV electro-optical sensors, direct view optics and a laser rangefinder/designator for targeting of the semi-active laser (SAL) guided Hellfire missile. The center display in figure 14 represents the TADS video. TADS can be "linked" to FCR-acquired targets for visual confirmation or a SAL Hellfire missile attack if visibility conditions permit. The system accuracy is sufficient to display the selected target in the narrow-field-of-view FLIR to speed confirmation/identification. TADS can also provide the targeting data required to fire the Longbow Hellfire missile. This high level of sensor integration provides the AH-64D with a unique capability to deal with adverse weather, obscurants, countermeasures or target area conditions.

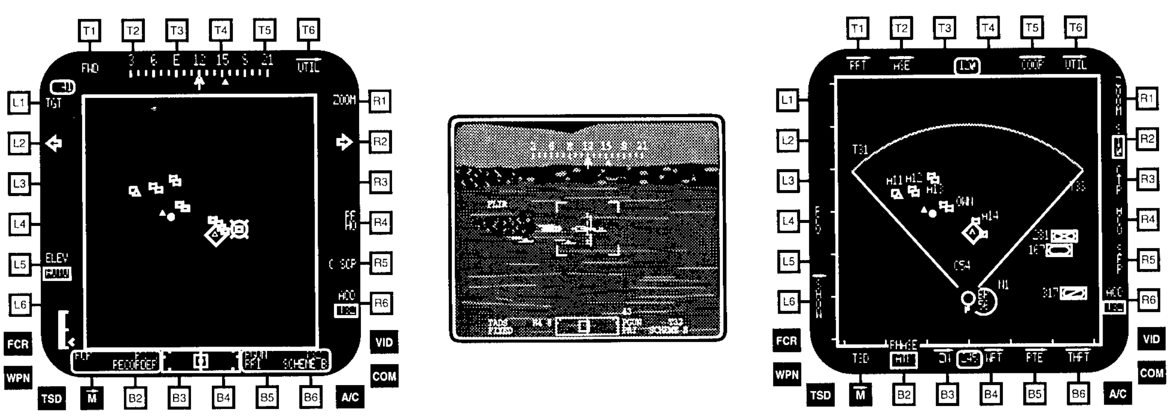

Figure 14. "See" the battlefield: Apache Longbow MPDs and TADS display (center)

8. DIGITAL CONNECTIVITY

As discussed earlier, the ability to "see" the battlefield and share near-real-time information with other members of the Combined Arms Team makes Longbow a true force multiplier. Having real-time battlefield information allows the ground commander to shape the appropriate response regardless of the scenario.

The Apache Longbow is on the forefront of digital communications among tactical U.S. Army platforms. As shown in figure 15, digital connectivity has been demonstrated with the J-STARS airborne platform, the Rivet Joint platform, the J-STARS ground station, the U.S. Army Aviation Command and Control (A2C2) platform, the maneuver control system (MCS/Phoenix), and a prototype ground command and control vehicle. Additionally, two Apache Longbows recently participated in the U.S. Army Warfighting Experiment call Force XXI. Needless to say, their performance was truly outstanding.

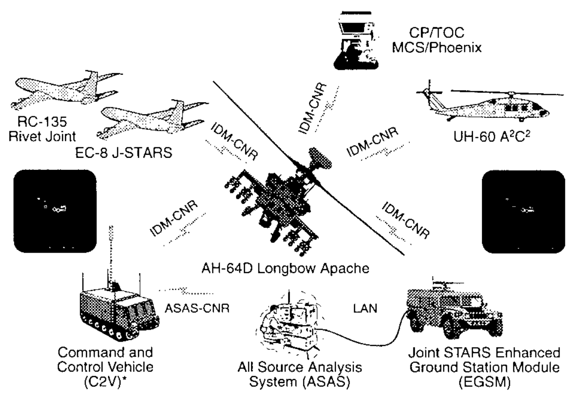

Figure 15. Demonstrated capability

The Apache Longbow incorporates a digital data modem that is capable of communicating virtually any information in the onboard processing centers to command and control centers over any of the onboard radios. This near-real-time information sharing capability enhances the situational awareness of the entire force allowing a proactive response within the decision cycle of any potential adversary.

9. BATTLE MANAGEMENT

The tremendous increases in effectiveness and aircraft survivability realized by the AH-64D Apache Longbow are only a part of the overall benefits it brings to the battlefield. The dramatic increase in situational awareness provided by the FCR search capability has been exploited in the AH-64D avionics architecture and crewstation design to provide a new dimension in battlefield management. The FCR targeting data displayed on the TSD, along with preplanned threat intelligence data and navigation data gives the team leader the ability to plan the local battle more effectively. The ability to transmit what he sees via the IDM makes the AH-64D a key element in the digital battlefield of tomorrow.

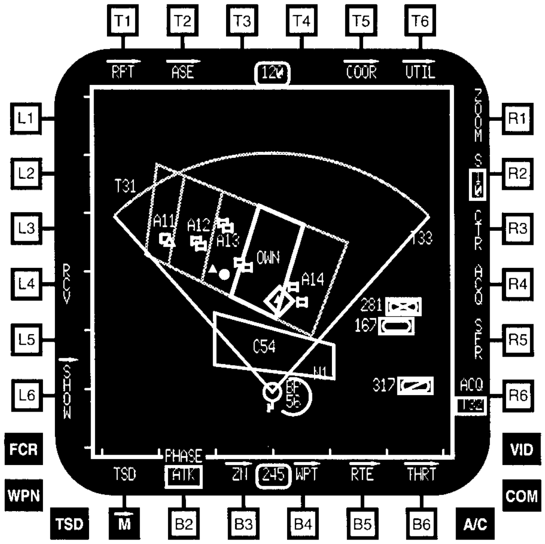

Figure 16. Battle coordination: tactical situation display

The TSD, figure 16, gives the team leader access to several unique features for automated battle management. Prebriefed friendly troop deployments and enemy troop dispositions can be called up on the display. All of the detected and classified FCR targets are displayed as the FCR scans. With this battle overview the team leader can reduce the probability of fratricide by drawing a no-fire zone (NFZ) around friendly troops. For fire distribution the team leader creates priority fire zones (PFZ) which partition the targets into precise areas for engagement by individual team members. The PFZs, the NFZ and the targets can be digitally transmitted with two keystrokes to other helicopters in the team or another IDM-equipped user on the radio net. When the attack commences, the FCR will prioritize targets within the assigned PFZ to reduce overkill. Targets within a NFZ will not be prioritized to help prevent fratricide. As the attack continues, the position of targets which have been shot at will be stored and displayed. This "shot at" file aids in battle damage assessment.

10. WEAPON SYSTEM INTEGRATION

The addition of the fire control radar (FCR) and the RF fire-and-forget missile was not a simple addition of another weapon on the Apache. The FCR and the RF missile were integrated into the total Apache weapons system. Simply put, the FCR and RFI added two additional sources of target information that were integrated with the existing sights and sensors. The target acquisition and designation system (TADS), the pilot night vision system (PNVS) and the integrated helmet and display sight system (IHADSS), for both the pilot and copilot-gunner, were accommodated in the integration activity. The objective was to maintain consistent crew selection logic regardless of sight and weapons system selection while reducing the workload through automation and cognitive aids. Similarly, the integration of the RF Hellfire missile was considered as an enhancement to the current capability and not merely a stand-alone capability. As a result, the totally integrated sight and weapon system currently supports the ability to engage multiple targets with any sight and weapon combination (figure 17) except for the Hellfire II missile that requires the laser.

Additionally, the sights can be employed in a cooperative mode through the link mode or independently by either crew member.

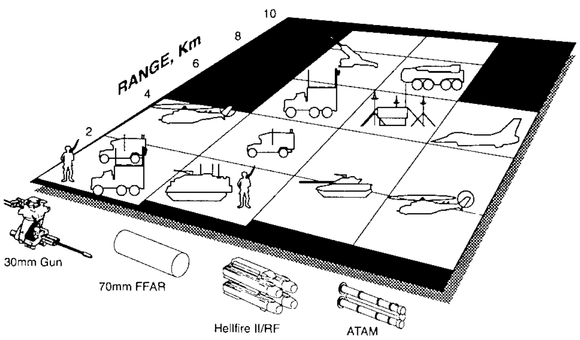

Figure 17. Fully-integrated long-range sensors and high-lethality weapons

The integrated sight and weapon subsystems provide the crew with the capability to select the appropriate sight, display and weapon for the tactical situation. In the MANPRINT crew station either crew member can operate the FCR and attack targets with the RF Hellfire missile, the 30mm cannon or 70mm rockets. The MPDs, the TADS handgrips, or the Collective mission grip provide controls and options for weapon system employment that enable either crewmember to employ the weapon system in conjunction with other tasks. Normally the CPG operates the system from the TADS handgrips and the pilot uses the collective mission grip. Selective use of automation has been employed to reduce crew workload. For example, when the FCR is selected as the sight, RF Hellfire missiles are automatically selected when a mixed load (SAL and RF) of Hellfire missiles are available. Similarly, when the TADS is selected as the sight, SAL missiles are automatically selected. Obviously, the crew can override either selection in real time or can tailor the system response based on their preferences.

11. PRECISION TARGETING

The FCR targeting data used to initialize an RF Hellfire missile consists of the target's position and velocity in aircraft referenced coordinates. The FCR is electronically boresighted to the aircraft navigation system automatically in flight to provide very accurate targeting data. The FCR targeting accuracy is sufficient to attack selected targets within a typical tactical vehicle formation. FCR target data can also be transmitted to another aircraft via the IDM for attack without reacquisition using the RF handover capability.

The Longbow Hellfire missile provides a true fire-and-forget capability in clear or adverse weather conditions and in the presence of battlefield obscurants such as dust or smoke countermeasures. Conditions which rapidly degrade a laser designator and electro-optical targeting sensors have little or no impact on the millimeter-wave radar guidance section. The Longbow weapon system has been designed to attack selected targets in closely-spaced tactical formations. Multiple missiles can be launched at the prioritized list of FCR-classified targets with high confidence that the selected targets will be killed. The fire-and-forget capability, combined with the high rate of fire, minimizes helicopter exposure for weapon delivery and gives the AH-64D Apache Longbow unprecedented survivability.

12. DEMONSTRATED RESULTS

The Apache Longbow operational test was conducted in two phases, at China Lake Naval Weapons Center and at Fort Hunter-Liggett California from January through March 1995. Six (three with FCR and three without) prototype Apache Longbows truly dominated the battlefield achieving a 400% better lethality and 700% better survivability than the combat-proven AH-64A against a robust 2004 enemy force. The most significant result, considering today's environment, is the absence of any fratricide incidents during all Longbow scenarios. In fact, the results were so overwhelming in favor of the Apache Longbow team, the test was stopped early – a first in the history of Army Operational Testing. The results of the U.S. Army Initial Operational Test and Evaluation are unarguable and documented. Figure 17 illustrates some of the more significant factors.

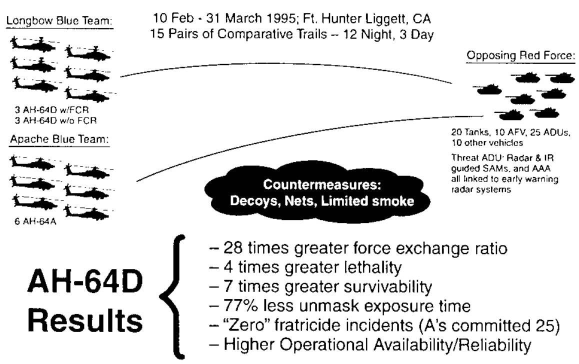

Figure 18. IOTE force-on-force phase results

The success of this test is a compliment to the advanced technologies that provided increased situation awareness, sensor and weapon system integration that provided the lethality and survivability and crewstation management that enable the efficient and effective operation of the system. It is also a compliment to the soldiers who operated the Apache Longbows and refined the tactics, techniques and procedures that were so successfully employed.

13. SPECTRUM OF CONFLICT

Military operations today and in the foreseeable future will span the continuum of activity levels from low intensity conflict to peacekeeping operations or even humanitarian operations (figure 19). Every level of the spectrum requires good and timely intelligence as well as the capability to rapidly respond to crises.

The challenge today is to blend the capabilities required for high intensity combat operations into the missions and requirements of today's environment. The new world order is forcing militaries around the world to focus on new challenges and make preparations to meet those challenges with current equipment and forces.

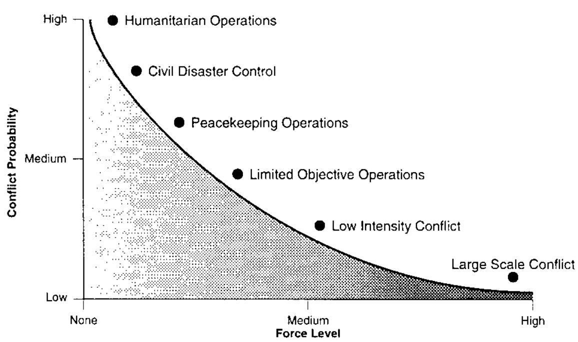

Figure 19. Spectrum of conflict

The combination of multi-spectral sensors capable of collecting information, the ability to display the information in a relational picture, the ability to distribute the information in near-real-time, in day, night and in adverse/obscured environments, and the ability to respond when required with deadly force, makes the Apache Longbow highly relevant across the entire spectrum.

14. PEACEKEEPING MISSION

There are three elements of today's peacekeeping mission. They are: protect your forces, provide deterrence and prevent escalation.

The Apache is a major player in each of these elements. The Apache provides the firepower, surveillance and rapid response capability to protect the force. The visible presence of the Apache is an ever-present message for deterrence. The ability to quickly respond with lethal force, should deterrence fail, enables the Apache to prevent escalation. Today, Apaches are being used in Bosnia in support of operation Joint Endeavor to enforce the peace and monitor activity in the defined zones of separation. On more than one occasion, Apaches have provided video from the onboard sensors to document treaty violations. A clear example of deterrence which prevents escalation.

Reconnaissance, intelligence, situation awareness are all valuable assets in any complex activity, military or civilian. The Apache Longbow's use of advanced radar, imaging systems and digital communications are just a few of the enabling technologies to meet the challenges of the 21st century. The nature of conflict is not changing but the emphasis our nation places on less intensive forms of military conflict and operations other than war must be considered in the development of future weapon system. The Apache has been a real success story for the Bosnia forces - they walk softly but carry a big stick. The Apache Longbow with its advanced capabilities will be even better.

15. SUMMARY

To summarize Apache performance, the AH-64D Apache has the built-in capability to think, to act, to assess, to react, to prioritize, to communicate, to maneuver, to threaten, to look after its crew and friendly troops on the ground, and to provide commanders with near-real-time battlefield information never before possible. Longbow's adverse weather performance, stationary target detection capabilities, automatic target classification, and fire-and-forget missile are breakthrough technologies unmatched by any other system under development. Simply put, the Apache Longbow has the capability to defend itself against the most lethal threats, support the commander's scheme of maneuver in any spectrum of conflict, provide a robust precision strike capability, and provide superior situational awareness.

WE PROMISED IT AND WE DELIVERED IT

Apache Longbow has:

- Increased situational awareness and control of the battlefield
- Demonstrated adverse weather, obscured battlefield capabilities with precision strike capability
- Improved lethality, survivability
- Enhanced reliability, availability and maintainability
- Initiated production...on cost and on schedule

Figure 20. The future is now

The AH-64D Apache Longbow is neither a mere concept nor a vision for the 21st century. It is a totally integrated, fourth-generation attack helicopter weapon system that represents information-age technology of the future. It is flying now, tested, demonstrated and in production. All as promised.

RAH-66 Comanche Case History

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1.0 SUMMARY

Combat helicopters perform two basic missions: attack and reconnaissance. The mobility, situational awareness, and firepower that combat helicopters provide ground forces was well demonstrated during the Vietnam War. Operation Desert Storm provided a glimpse of modern nonlinear, close combat, coalition warfare and reinforced the importance of advanced technology combat equipment.

Most of the U.S. Army reconnaissance and light attack helicopters were built during the Vietnam era. These aircraft lack much of the technology needed during Operation Desert Storm to ensure operational success. Technology features unavailable include:

- Night sensors (targeting and pilotage)
- Navigation equipment
- Communication gear
- Ballistic tolerance
- Biological and chemical protection
- Hot/High performance
- Extended range
- Armament

The U.S. Army has implemented a modernization strategy to replace its older assets with systems that are versatile (capable in many different situations), and robust (capable under uncertain conditions within a situation). In addition, the new aircraft will be able to leverage other battlefield systems to assure decisive warfighting capabilities for the highly uncertain new global battlefield environment. Comanche is the advanced technology armed reconnaissance combat helicopter, designated to replace the current Army reconnaissance helicopters. Developed through an evolutionary series of analysis, simulations, tests, and demonstrations, the Comanche Weapon System integrates many new advanced technologies to provide a quantum leap in operational capability and a combat system that far surpasses existing helicopters, in terms of survivability, versatility, lethality, reliability, and cost of ownership. Comanche is specifically designed to operate and survive on the modern, combined arms, digital, high-tech battlefield. Comanche's low-observable (LO) characteristics protect the element-of-surprise during maneuvers by reducing the detectability of the aircraft. Comanche's advanced sensor suite provides the aircraft "effective standoff," allowing it to remain covert while still operating within onboard armament system range. This capability also allows the pilot to close on the target to a range necessary to correctly identify the targets and effectively reduce fratricide under nonlinear operation. The Comanche's advanced digital communication and navigation system makes Comanche the targeting element for the Army's long-range advanced shooters, such as the multiple launch rocket system (MLRS) and the Army Tactical Missile System (ATACMS). Comanche is on track to address the reconnaissance role for the Army and to be the attack helicopter of the 21st century. Innovative technology and extensive use of simulation have produced an advanced armed reconnaissance helicopter, the Comanche, which will save lives, increase mission effectiveness, and reduce cost of ownership.

This paper will focus on the case history of the RAH-66 Comanche and some of the specific solutions to the weapons systems integration problems.

2.0 COMANCHE PROGRAM BACKGROUND

The RAH-66 Comanche is the Army's newest reconnaissance helicopter, designed to operate with a minimal logistical burden while serving as the commander's eyes in the 21st century battlespace. It replaces the current light fleet of tactically obsolete OH-58 and AH-1 helicopters for the primary missions of armed reconnaissance and light attack, with embedded air combat capability. The RAH-66 will provide increased combat effectiveness and battlefield survivability, and will modernize the Army's scout and light attack assets. Comanche will be easily sustained requiring fewer personnel and support equipment, and will provide a decisive battlefield capability in day, night, and adverse weather operations. The system will provide an unprecedented level of operational flexibility and survivability to the battlefield commander. An all composite LO airframe with retractable weapons and integral third-generation infrared (IR) suppressors makes the Comanche weapon system hard to detect and engage, increasing aircraft and crew survivability. An advanced technology bearingless main rotor (BMR) system and large diameter FANTAILTM antitorque system provides the maneuverability and agility necessary for night nap-of-the-earth (NOE) flight. Comanche has been designed to be exceptionally maintainable and easily transportable. Through its keelbeam construction, numerous access panels, easily accessible line-replaceable units/modules, and advanced diagnostics, the RAH-66 possesses designed-in maintainability. Comanche aircraft will be capable of being rapidly loaded into, or unloaded from, any of the Air Force transport aircraft. The RAH-66 Comanche is designed and developed by a joint venture of Boeing Defense & Space Group, Helicopters Division and the Sikorsky Aircraft Corporation, a United Technologies Company.

System Capability. Comanche will correct light fleet deficiencies such as marginal night and adverse weather capability; location/navigation inaccuracies; inability to self-deploy to overseas theaters of operations; inadequate reliability, performance, and survivability; and high operating costs. System improvements include lightweight composite airframe structures; a protected antitorque system; low-vibration, high-reliability rotor system; second generation target acquisition and night vision sensors; and an advanced electronics architecture. Comanche has an integrated, automated cockpit, worldwide navigation capability, secure communications, and electromagnetic pulse and interference-hardened avionics. It incorporates crashworthy design features; wheeled, retractable landing gear; and will be self-deployable to Europe, the Middle East, and Latin America. Comanche will perform both reconnaissance and attack missions, utilizing aided

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multiple target acquisition, classification, prioritization, and handover capabilities. It will have a dash speed in excess of 170 kn and a vertical rate-of-climb in excess of 500 feet-per-minute at high-altitude/hot-day conditions (4,000 feet and 95°F). Armament features include fire and forget radio frequency (RF) and semiactive laser HELLFIRE missiles, air-to-air (ATA) Stinger missiles, 2.75" rockets, and a 20 mm turreted gun. Comanche will be integrated within the Army Aviation force structure to compliment the AH-64 Apache helicopter in heavy divisions, and provide armed reconnaissance and attack capabilities in light divisions.

2.1 Program Life-Cycle Phases

The Comanche program is currently in the demonstrative/validation (Dem/Val) phase of the acquisition life-cycle. Approval was received in June 1988 to begin the Dem/Val phase, and two initial competitive Dem/Val phase contracts were awarded to two separate contractor teams. In April 1991, a downselect to one contractor was made to complete the LHX/Comanche development efforts. A Dem/Val contract, scheduled to be completed by the end of 1994, was awarded to Boeing Sikorsky with continuation to be authorized following a successful milestone decision, through a priced option. There have been several restructures of the program, due to funding changes, that have required significant modifications to the Dem/Val contract. In 1992, the program was refocused to a pure Dem/Val effort and the period of performance was stretched. The original priced full-scale development option was deleted. The more recent program change resulted from an acquisition decision memorandum (ADM) issued on 21 March 1995. This changed the program strategy to a two-prototype aircraft Dem/Val development phase with six additional aircraft for use in demonstrating the effectiveness of Comanche in the Army's reconnaissance mission role. These aircraft are called early operational capability (EOC) aircraft because they will be used for limited field testing by the Army prior to low-rate initial production (LRIP). The first Comanche prototype was rolled out on May 1995. An extensive preflight qualification program, and a 50-hour preflight acceptance test on the tie-down propulsion system test bed (PSTB) which demonstrated the successful integration of all dynamic system components, was successfully completed in 1995. First flight occurred on May 4, 1996; and featured 36 minutes of flight, including two takeoffs and landings, hover turns, a: d forward flight. This event marked the beginning of an extensive envelope expansion program that has taken the aircraft to over 160 kn.

Demonstration/Validation (Dem/Val). The Dem/Val phase continues until October 2001. During the remaining Dem/Val time frame, emphasis will be placed upon validating the capability of the weapon system design. This will include the design and development of the reconnaissance mission equipment package (MEP); in particular, the target acquisition system, the night vision pilotage system (NVPS), the integrated communication system, and the helmet-mounted display (HMD). Prototype number one flight testing will focus on demonstrating the capabilities of the air vehicle, including further envelope expansion, flight and handling qualities, and subsystem integration. Flight testing of prototype number two will focus primarily on integration and demonstration of the reconnaissance MEP. The program will also initiate the design of the armed reconnaissance/light attack MEP, which includes primarily the capability to fire HELLFIRE and Stinger missiles, rockets, and a 20 mm gun. Surveys of the signature characteristics of the aircraft, as well as a full-scale radar cross section (RCS) model, will identify any corrections necessary to proceed into production.

Engineering and Manufacturing Development (EMD). The EMD phase of the development program will begin after a successful Milestone II decision. During EMD, the design and development of the armed reconnaissance/light attack MEP will be completed. The six EOC aircraft will undergo a field employment exercise and user evaluation. Following field employment, two of the EOC aircraft will be used for component, subsystem, and flight-test evaluation of the armament and fire control systems. Two of the EOC aircraft will be used for Longbow (LB) integration and development testing. Additionally, two EOC aircraft will be retained by the user for introductory crew training prior to the initial operational test and evaluation (IOTE). One of the improvements to the original EOC concept is the use of LRIP aircraft for IOTE, rather than the EOC aircraft. Since one of the important characteristics of the RAH-66 is less required supportability than today's helicopters, it is important that the actual production configuration be tested during IOTE. The limited field test evaluation concept (prior to production configuration finalization) dramatically reduces the risk of building a production configuration requiring design, technology, or material changes soon after fielding.

Early Operational Capability (EOC). A key element in the current acquisition strategy is the user field evaluation of the development aircraft, prior to a final decision on the production configuration. The configuration of those early development aircraft include the reconnaissance mission equipment, with no armament. An EOC preliminary design review is scheduled for in October 1997, followed by an EOC critical design review (CDR) in September 1998. Beginning in FY2002, the Government will take delivery of the six EOC aircraft for field employment and evaluation of their reconnaissance capabilities. All six EOC aircraft will remain employed in the field during FY2003 to 2004, so that a warfighter evaluation of capability and suitability can be conducted by Army pilots.

2.2 Production Phase

Low-Rate Initial Production (LRIP). As stated above, one of the important improvements to the Comanche acquisition strategy is the decision to use LRIP aircraft for IOTE, rather than EOC aircraft. Preliminary LRIP activity will begin immediately following field employment of the EOC aircraft, and completion of the initial limited user testing (LUT). A request for proposal (RFP) for long-lead items will be released in the fourth quarter of FY2001, and contract award for the first lot is scheduled for November 2003. Ten aircraft are required to support IOTE, leaving 14 aircraft to complete the planned delivery of lot 1 aircraft. Accelerating 10 aircraft will provide a more gradual start up of the production process, allowing delivery of the first 24 aircraft over 24 months rather than 12 months. The use of the LRIP aircraft for IOTE will provide the operational tester a greater opportunity to evaluate and understand how to best use the production RAH-66 in a combat environment.

Full-Rate Production (FRP). A Defense Acquisition Board (DAB) Milestone III review is scheduled to occur in December 2006, with a concurrent contract award for FRP beginning with 44 aircraft (Lot 4). The number of aircraft will ramp-up to 60 in Lots 5 and 6, and then 72 aircraft will be produced in each of Lots 7 through 21 for a total of 1,292 aircraft.

3.0 COMANCHE AIRCRAFT OVERVIEW

The RAH-66 is a twin 1380-hp turboshaft engine, two-seat (tandem) helicopter design. The T800 engines provide power to an advanced technology, split-torque main gearbox which drives a five-bladed, bearingless, composite main rotor and a FANTAILTM antitorque system. Significant system and key design features for the Comanche include: low signature (radar, visual, infrared, and acoustic); improved target acquisition sensors; increased maneuverability, agility and speed; increased survivability; significantly reduced operation and support costs; and reduced supportability requirements (simple remove and replace maintenance concept).

As indicated in Figure 1, the RAH-66 has five durable all-composite rotor blades; a highly reliable BMR head; a compact transmission; multiservice communications and datalink antennas; a shrouded high-thrust tail rotor; engine exhaust IR signature suppression; LO composite structure; easy-access aft electronics bay; internal weapons carriage, retractable landing gear; high reliability electronics in easily accessible bays; computer-driven battle management; a 20 mm turreted gun; long-range IR/TV targeting sensors; infrared/low-visibility image intensifier pilotage sensors; and HMDs for head-up flying.

3.1 Airframe Materials

In the airframe, composites are used in the skins, doors, frames, bulkheads, internal center keelbeam box structure, main rotor pylon fairing, FANTAIL shroud, vertical pylon, and horizontal stabilizer, as shown in Figure 2. The major composite material used include new toughened epoxy resins, bismaleimide resins, and graphite fibers with improved stiffness and strain allowables. Figure 3 shows Comanche's dramatic shift away from aluminum usage, and instead towards the use of composites.

With the composite materials, the airframe modular design concept results in a structural weight approximately 23% lighter than an equivalent metal design.

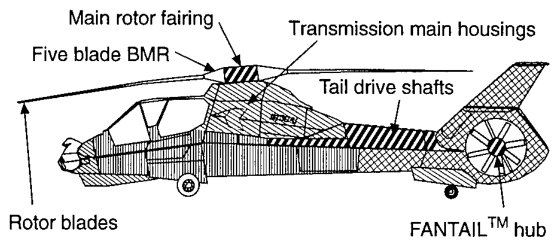

Figure 2. Comanche Airframe Design

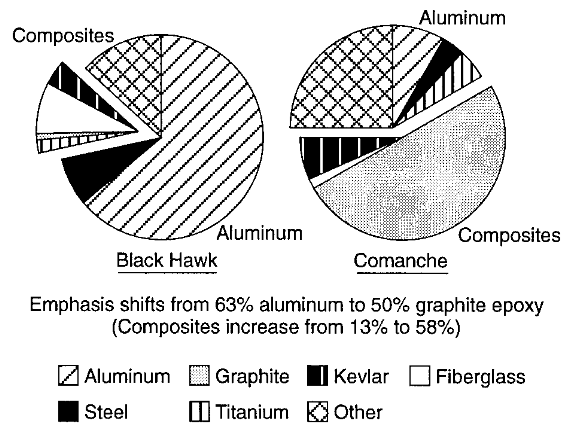

Figure 3. Comanche Airframe Material Usage

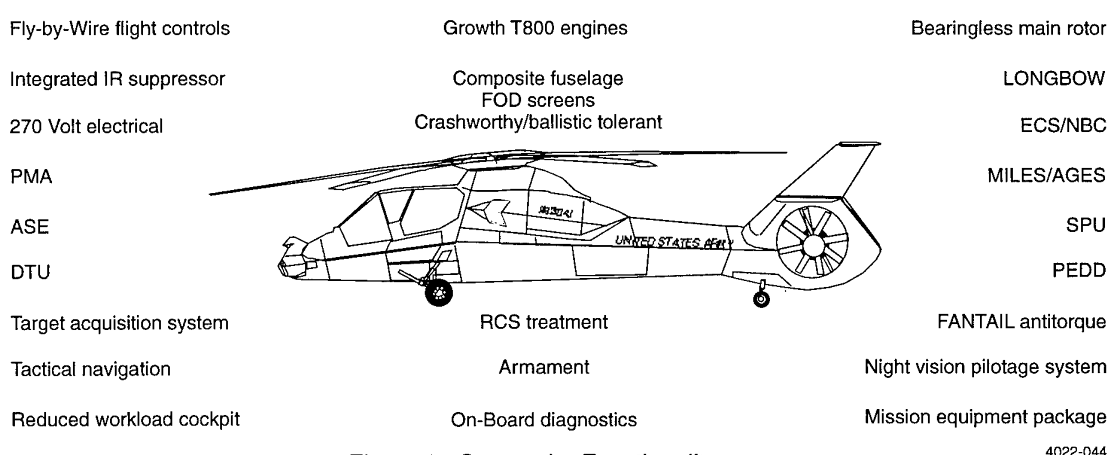

Figure 1. Comanche Functionality

3.2 Dynamic Systems

Main Rotor. Vertical-flight performance capability of the Comanche results from sizing the rotor to meet the performance weapon system specification (PWSS) maneuver requirements. The maneuver requirements and the main rotor necessary to perform the PWSS maneuvers are presented in Figure 4.

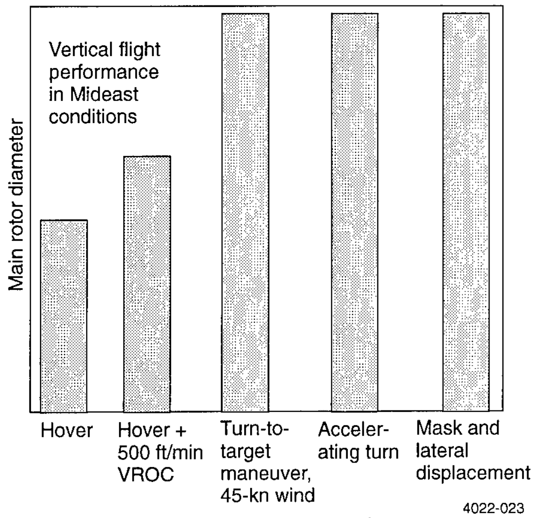

Figure 4. Main Rotor Sizing

As shown is Figure 5, isolated main rotor hover performance tests show a 72 kg (159 lb) higher capability than was demonstrated during the 1/4 and 1/3.5-scale powered model testing. Flight testing of the Prototype aircraft, which operates at a 5,579 kg (12,300 lb) gross weight, carrying 925 kg (2,040 lb) of flight-test instrumentation and equipment, shows that the aircraft meets the predicted forward-flight performance, (see Figure 6). The aircraft was flown for the first year with the landing gear fixed down, while the triply redundant fly-by-wire flight control system (FCS) tests were conducted for the first time on the aircraft. In March 1997, the landing gear was retracted and the impact of the drag reduction is shown in Figure 6.

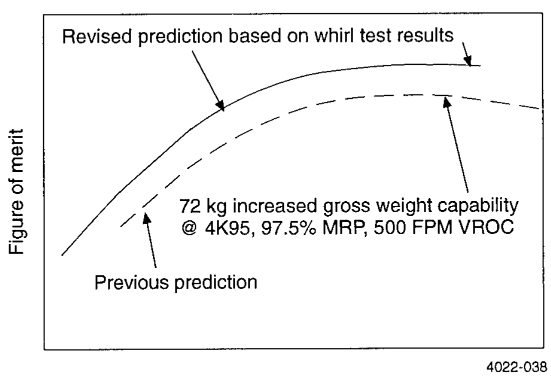

Figure 5. RAH-66 Isolated Main Rotor Hover Performance M_{Tip} = 0.628

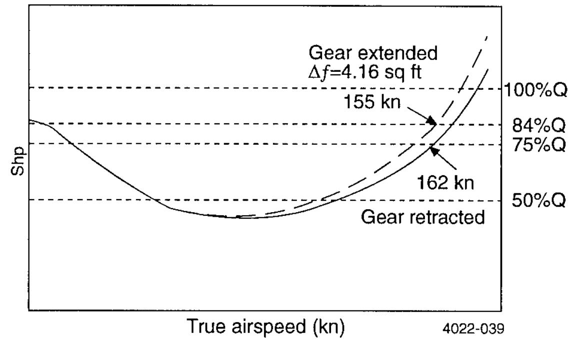

Figure 6. Level-Flight Performance

The Comanche main rotor system employs a five-bladed BMR with a 10.4% equivalent hinge offset, shown in Figure 7. This design reduces the rotor's acoustic signature and meets the high maneuverability, high performance, and survivability requirements necessary for air-to-ground combat, and terrain avoidance and NOE operations where the threat of ballistic damage is high. This simple, easily maintained, and highly survivable design also meets the military specification ride comfort requirements. Figure 8 shows the vibration characteristics of Prototype number one meet the Comanche production requirements. Crew comfort and workload is heavily influenced by the vibration environment in the cockpit. The Comanche 5-blade main rotor system produces a very low vibration environment when compared to other production combat reconnaissance aircraft. There is no vibration attenuation hardware on prototype number one, and none planned for Comanche in the future.

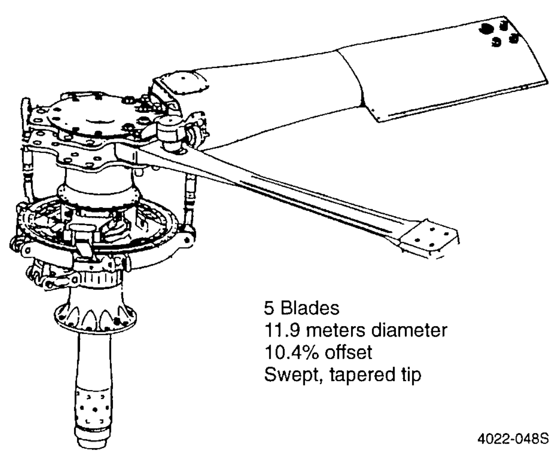

Figure 7. Bearingless Main Rotor

In a bearingless design, the composite flexbeam is tailored to accommodate flapping, lead-lag, and pitch motions of the blade. The flexbeam connects the rotor blade to the hub, and control inputs are transmitted to the blade through a torsionally stiff torque tube that surrounds the flexbeam. Each blade has a single flexbeam that bolts to the titanium hub at the root end, and is bolt-

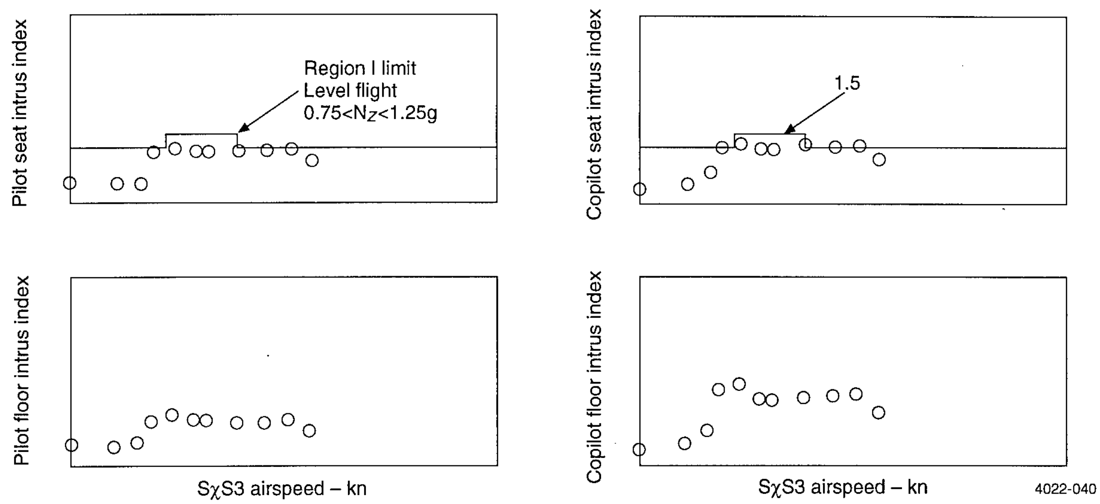

Figure 8. Intrusion Index Requirements Satisfied for Level Flight to V=100 kn

ed to the blade at the outboard end. Use of graphite cross-plies provide local reinforcing where the flexbeam attaches to the hub.

The Comanche main rotor blades, torque tube, flexbeam, and quill shaft are all made of composite materials, as shown in Figure 9. The rotor system has viscoelastic lag dampers and elastomeric bearings at the ends of the control rods. This carefully selected mix of materials results in a damage-tolerant design with benign failure mechanisms, making this rotor particularly survivable after combat damage.

Component	Fiber System	Resin System
Blades	Graphite and Fiberglass	Epoxy
Quill Shaft	Graphite tows and unidirectional broadgoods	Bismaleimide Resin
Torque Tube	Graphite tows and unidirectional broadgoods	Epoxy
Flexbeam	Fiberglass and Graphite	Epoxy

4022-047

Figure 9. Comanche Main Rotor Composite Materials Usage

3.3 FANTAIL™

The FANTAIL antitorque system was chosen for the Comanche because of its superior maneuverability and signature characteristics. The 13° canted design incorporates features to reduce the aircraft's acoustic signature. The FANTAIL design provides eight high aspect ratio blades operating at a low tip speed of 646 feet per second (197 meters per second). The design also incorporates a relatively large spacing between the fan blades and their support structure, which reduces interaction tones.

The helicopter is capable of completing a 180° turn-to-target maneuver in less than five seconds with winds up to 45 kn from any direction.

A full-scale prototype of the Comanche FANTAIL was built and tested on a S-76 aircraft with impressive results, see Figure 10. This aircraft achieved sideward and rearward flight speeds of 70 kn, and demonstrated a hover yaw acceleration of 0.86 radians/second to meet the Comanche 180° turn-to-target maneuver, with a comparably similar power consumption of a conventional tail rotor.

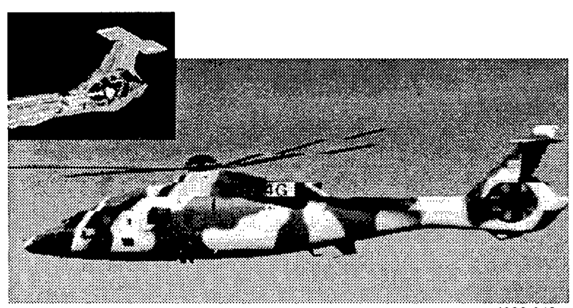

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Figure 10. S-76 FANTAIL Demonstrator Aircraft

Drive Train Technology. The split-torque main gearbox has a compact, simple, low maintenance, lightweight design, shown in Figure 11. The main gearbox includes a dual-engine rating of 2,198 hp and a single-engine rating of 1,430 hp. The split torque concept provides two load paths from each engine to the final bull gear stage. This concept enables engines to retain a high rpm and low torque until the final bull gear stage. Taking an 11-to-1 reduction at the final stage results in a lower weight and very compact size for such a high power gearbox. Fabrication of gears from high-hot-hardness steels also reduces gearbox weight. This design also permits the use of plug-in, direct-drive accessories, which further reduce weight, cost, and complexity.

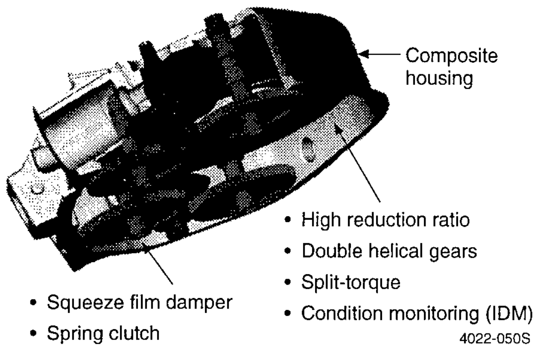

Figure 11. Comanche Drive Train Technology

Current production over-running clutches generally operate at speeds under 12,000 rpm, well below the optimum speed for achieving the lowest weight and most compact design. Comanche uses a spring clutch with a helical coil expanding against a bore to provide frictional drive. Operating at 23,000 rpm, this clutch design resulted in a 3% reduction in main gearbox weight, due to the lower torque operation at this high rpm. Costs are also lower, resulting from reducing the number of clutch parts from 33 (for a comparable ramp roller clutch) to only 8 for this design.

3.4 T800 ENGINES

The Comanche is powered by two LHTEC T800-LHT-801 engines, Figure 12, each providing 1,037 hp at a 30-minute intermediate-rated power (IRP) rating, and 1,123 hp at a 10-minute maximum-rated power (MRP) rating, at an altitude of 4,000 feet (1,220m) and an ambient temperature of 95°F (35°C). The engine design is modular and incorporates two centrifugal compressors with integral lubrication system and inlet particle separators.

The Comanche engine control system is coupled to the FCS providing better anticipation of rotor load demands, as well as improved rotor speed control under varying load conditions. The integrated fuel and FCS provides the following major features:

1. Collective pitch control anticipation to enhance main rotor speed control.
2. A lateral control rate anticipator to predict power changes and reduce transient torque spikes.
3. A yaw command rate anticipator to prepare for large anti-torque system loading and minimization of rotor speed decay.
4. Load factor enhancement which increases reference rotor speed when load factor is demanded, allowing more maneuverability at reduced rotor loads.

3.5 MANUFACTURING TECHNOLOGIES

The extensive use of advanced technology in the Comanche design was contingent upon developing a producible system meeting stringent design-to-cost goals. The air vehicle design, manufacturing, and producibility concepts were developed concurrently using integrated product development teams. One of the major enabling technologies used to produce these advances is provided through the extensive implementation of three-dimensional (3-D) software such as CATIA and PRO-E models for engineering design; rule-based technology (RBT); process control, numerically controlled programming, and tool design. A common 3-D electronic database used by all product development team members, resulted in a seamless data transfer from design to manufacturing, shown in Figure 13.

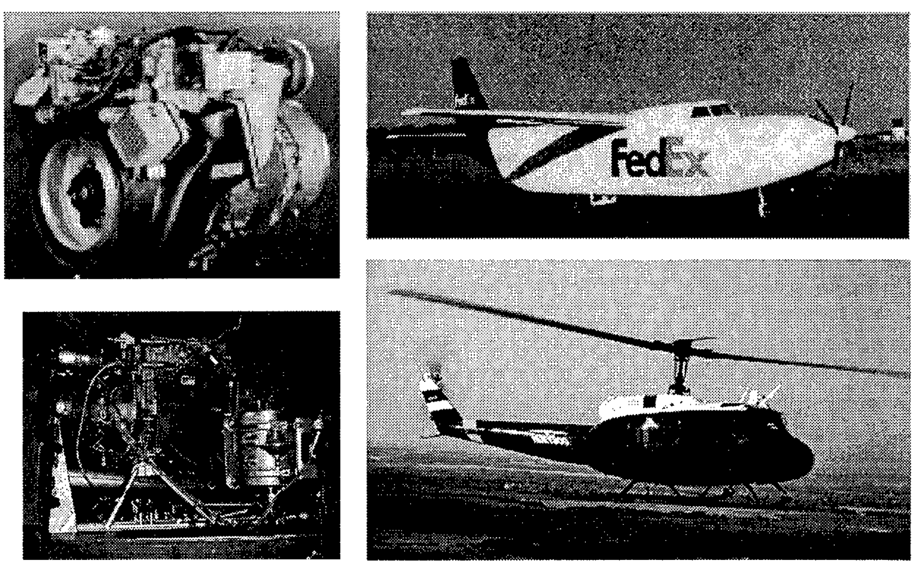

Figure 12. T800 Program

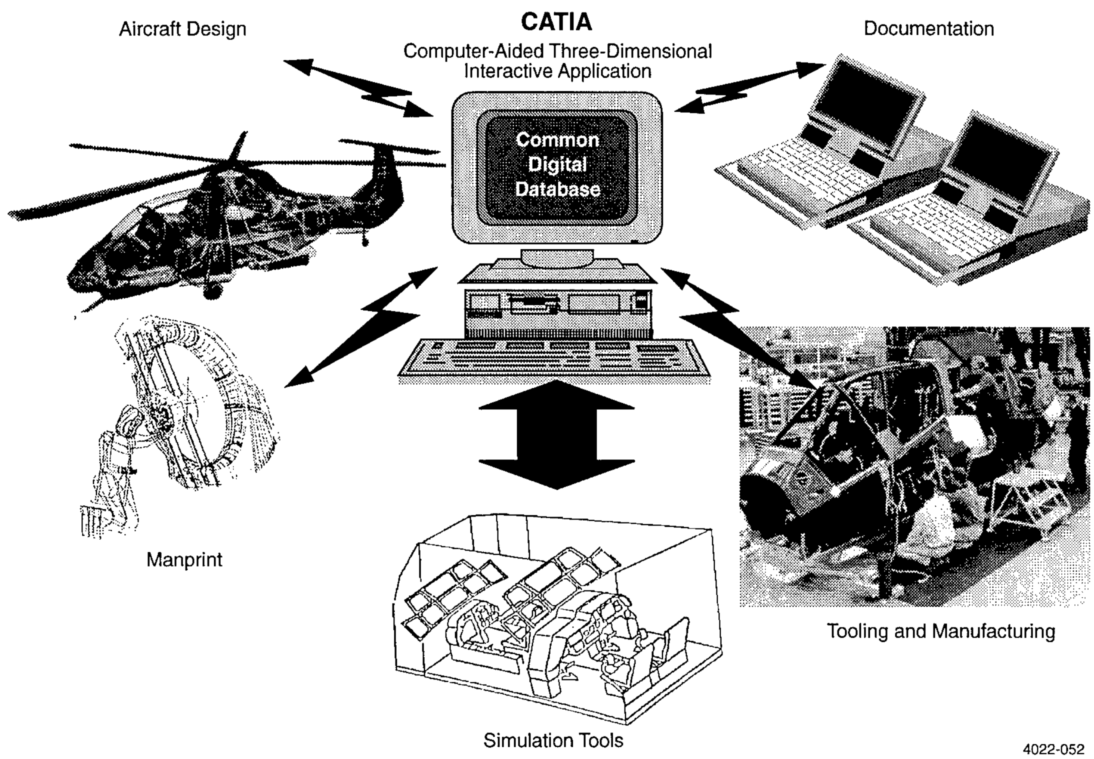

Figure 13. Digital Design Process

Under the Comanche program, airframe engineering master drawings are replaced with electronically dimensioned, toleranced drawings with datum at key part features allowing coordination of the tooling, assembly, and parts inspection through final assembly. Electronic data, created by a 3-D computer-aided design (CAD) system replaces the physical master model. This 3-D database allows the manufacturing engineer to develop pictorial process plans, numerically controlled machining programs, and "masterless tooling," working directly from the same database that the designer used to create the part. A comprehensive and detailed building-block approach to design, analysis, and test was mandatory to reduce program risks associated with new technology integration into new manufacturing approaches, shown in Figure 14.

The airframe design focused on the modular assembly. An approximately 24 foot (7.3 meter) long keelbeam box structure is manufactured using two linear co-cured keelbeams assembled to a lower skin panel by various cross-frame and bulkhead subassemblies. The keelbeam takes all the airframe loads. As a result, airframe skins are a secondary structure, and can therefore accommodate the large number of fuselage cut-outs without the weight penalties occurring in a semimonocoque construction.

Comanche has pioneered the use of lightweight honeycomb core that is only 60% as dense as the core found in older designs. This is possible through the use of new techniques that eliminate core crushing problems in curing low-density core in the autoclave. The result is a lower-weight airframe.

3.6 FLIGHT CONTROLS

The Comanche FCS is a triply redundant, functionally partitioned, fly-by-wire system, which gets its sensor data from a digital data bus. In the cockpit, the pilot has a sidearm controller, and a displacement collective pitch control, shown in Figure 15. The sidearm controller provides pitch, roll, and yaw control, and has limited control authority in the vertical axis that acts like a collective pitch "beeper." When the pilot pulls up on the sidearm controller, the aircraft rises slowly; when he pushes down on it, the aircraft stops climbing. All actuators are jam-resistant, dual hydraulic actuators with redundant control valves. Electrical and hydraulic power sources are redundant as well, and all critical components are strategically separated from each other to enhance ballistic protection. The FCS is also shielded to provide hardening against electromagnetic interference, lightning, and nuclear radiation. A two-level maintenance diagnostic system has been demonstrated to have a 99% accuracy in fault detection, and a 98% accuracy in fault isolation. Predicted flight safety and mission reliability greatly exceed their respective requirement allocations. A schematic of the FCS is shown in Figure 16 and its functional partitioning is depicted in Figure 17.

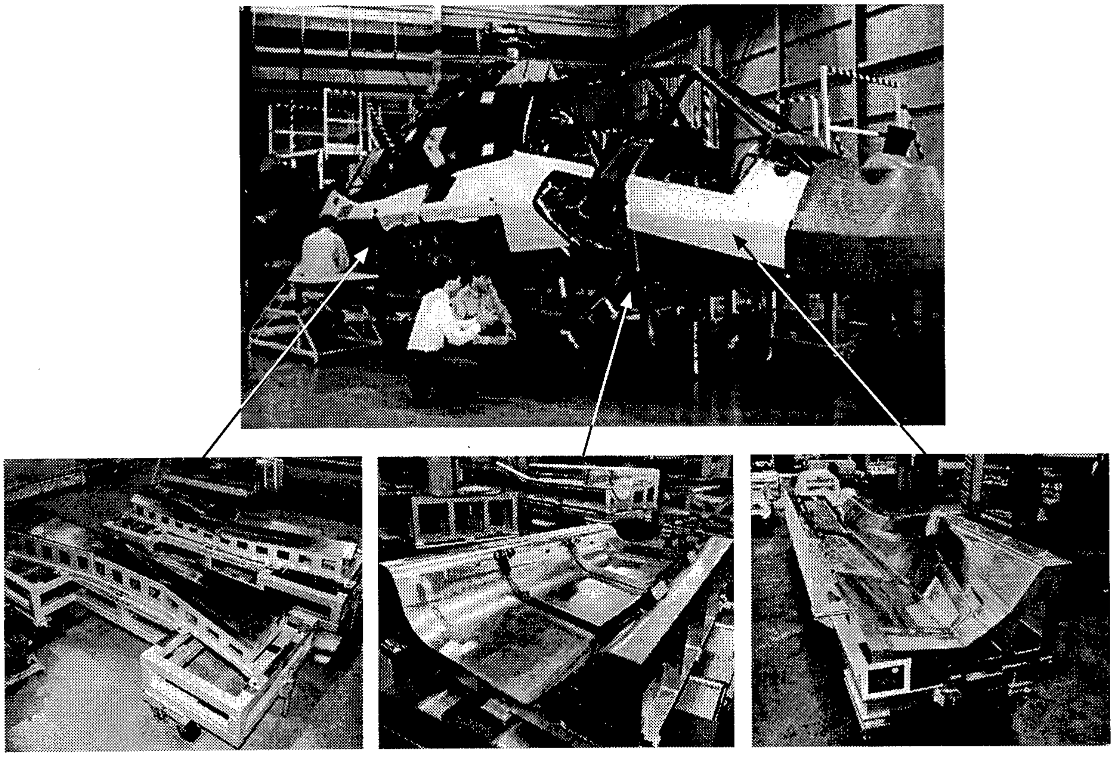

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Figure 14. Composite Tools

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Figure 15. RAH-66 Commanche Crew Station

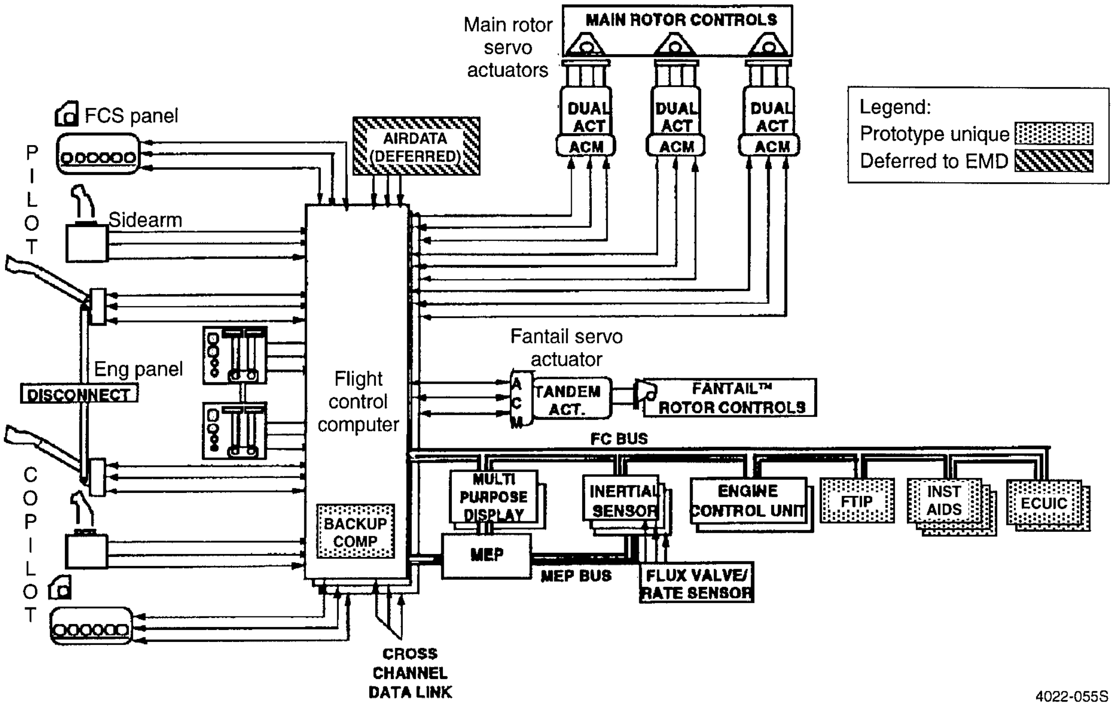


Figure 16. Comanche Flight Control System (FCS) Schematic

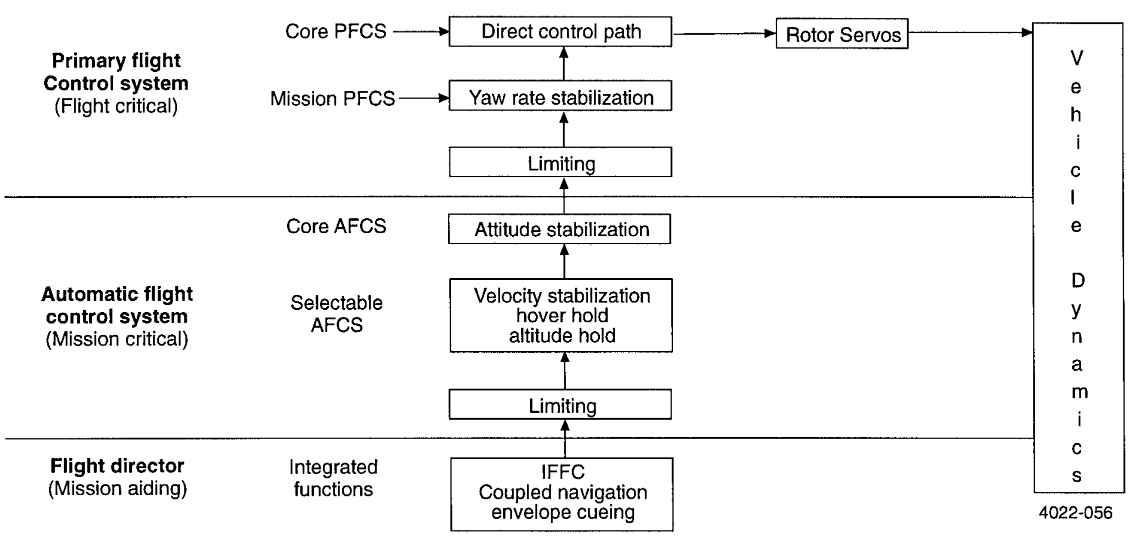


Figure 17. Comanche Flight Control System (FCS) Partitioning

3.7 MISSION EQUIPMENT PACKAGE (MEP)

By combining very high-speed integrated circuit (VHSIC) technology with parallel processor technology, Comanche achieves a data processing throughput capability of 150 million instructions per second (MIPS). The Comanche MEP architecture is shown in Figure 18.

The Comanche computer processing and MEP functions are not accomplished in traditional "black boxes" operating in a federated system, but in two racks of electronic modules located on each side of the aircraft. Each rack is populated with standard electronic modules--E format, Figure 19. The modules perform signal and data processing, as well as video graphics generation. Each module is interconnected through a common "motherboard," and appropriate high-speed data buses. The mission computers are connected to the other MEP components through a series of fiber optic and conventional wire data buses. The MEP electronic hardware is also implemented on SEM-E modules. In all, there are approximately 190 modules throughout the aircraft. The mission computer modules employ a unique design approach which includes "multichip packages" (MCP) in which the individual semiconductor devices are mounted in solderless, removable

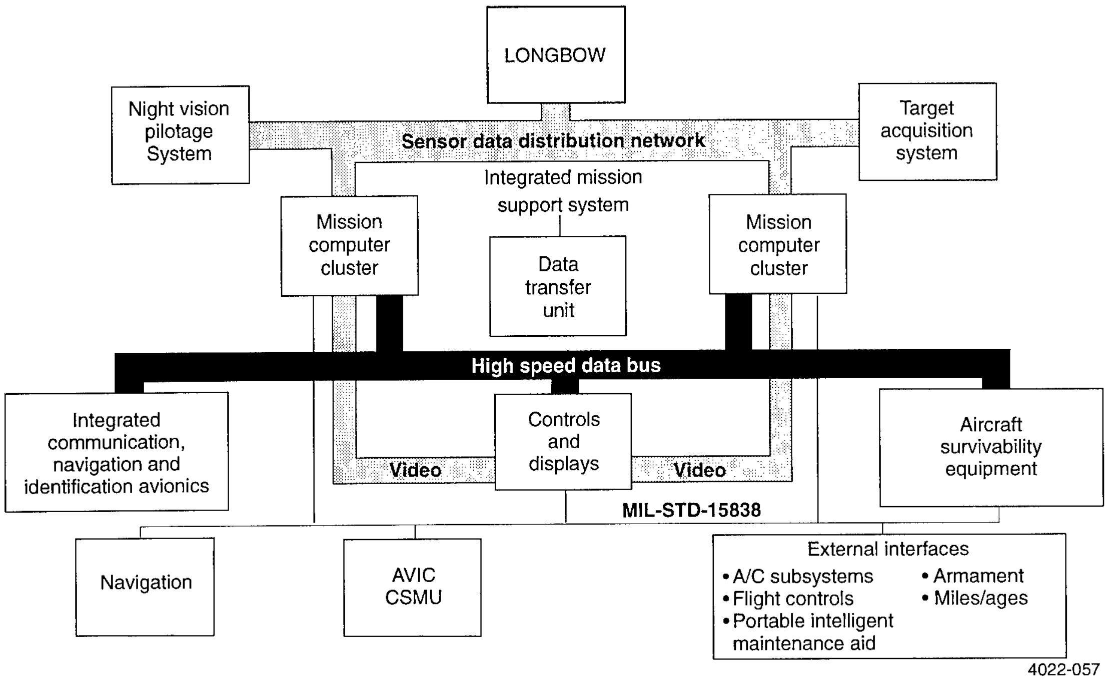


Figure 18. Comanche MEP Architecture

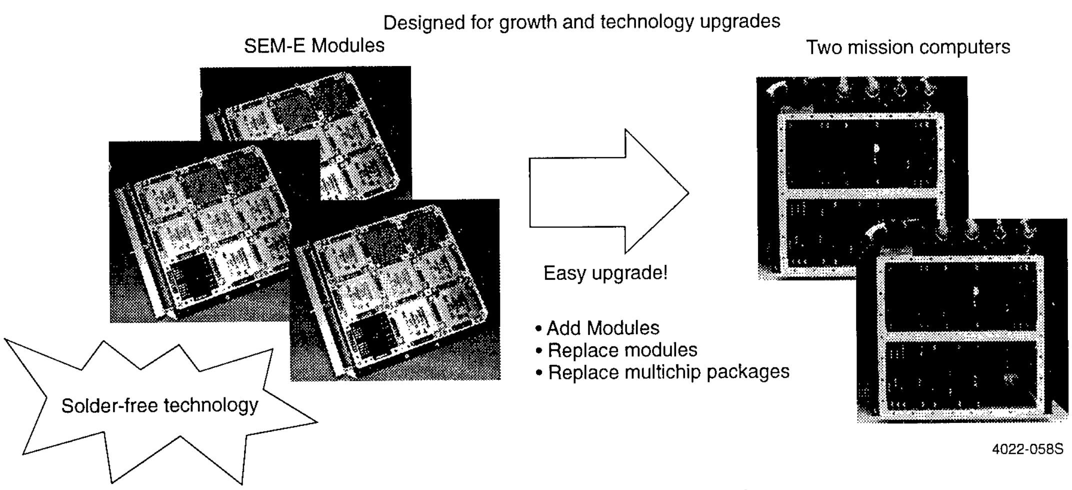


Figure 19. Commanche Processing

packages that can be easily changed. As electronic technology progresses over the years, these modules can be replaced with the latest technology. In the development program to date, data processor modules were updated once to incorporate a newer processing chip and higher density memories. The hardware change made to the prototype had very minimal impact to the program. Another processor technology upgrade is planned for EOC.

Comanche's sensors are its eyes and ears. The second generation focal plane array forward looking infrared (FLIR) technology embodied in Comanche has more than 40% better range performance compared to earlier FLIRs, providing for increased operational standoff range and survivability.

The electro-optical sensor system (EOSS) is located in the nose of the aircraft, Figure 20. The EOSS consists of the electro-optical target acquisition and designation system (EOTADS) and the NVPS.

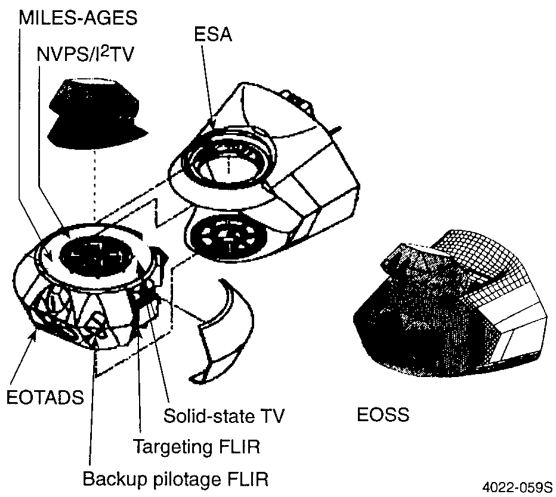


Figure 20. Integrated EOSS Design

The EOTADS is an on-turret, stabilized, multifunction electro-optical system containing a day/night thermal imaging FLIR sensor, a solid state television camera, and a laser range finder/designator. The EOTADS enables the crew to detect, classify, recognize, track, identify, and engage targets using manual and aided search modes.

The FLIR uses state-of-the-art, second generation, time delay integration detectors for thermal imaging in the 8 to 12 micron wavelength region. The EOTADS is integrated with the aided target detection/classification (ATD/C) and automated target tracker (ATT) to provide the capability to perform automated wide area searches, storing the imagery for recall by the crew, or for automated target detection and classification. The EOTADS has three fields of view: two for targeting, and one wide field of view with unity magnification for backup pilotage.

The NVPS consists of a second generation FLIR (similar to the EOTADS FLIR), and a solid-state image intensified television (IITV) providing complimentary night vision capability. The FLIR and IITV sensors are located in a helmet-slewable stabilized turret located on top of the EOTADS.

NOE flight in a combat environment is extremely dangerous and demanding of pilot skills. The pilot must have his eyes out of the cockpit, yet still have access to important flight instrumentation and MEP sensor data. Comanche's systems accommodate these requirements through the helmet integrated display and sighting system (HIDSS), Figure 21. The HIDSS is a biocular, HMD providing the Comanche crew members with a heads-up, eyes-out capability for pilotage and weapon sighting activities. The FLIR, IITV, and 20 mm Gatling gun are all slaved to the HIDSS and points wherever the pilot looks.

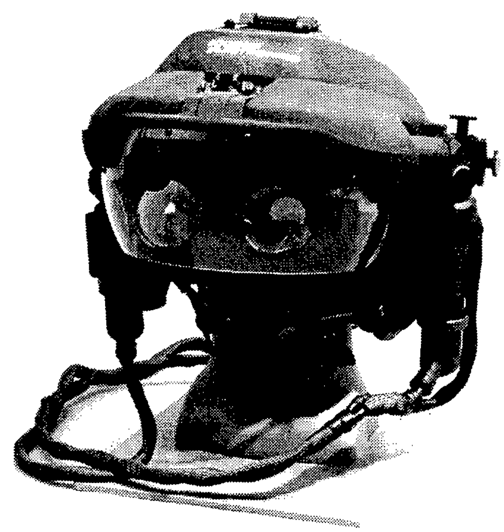


Figure 21. Comanche Helmet Display

3.7.1 Cockpit Displays

A layout of the two Comanche multifunction cockpit displays is shown in Figure 22. The right multifunction display is a 6- by 8-inch (150 mm by 200 mm) high resolution, color, active matrix liquid crystal display unit used primarily for instrument graphics and map displays. The left multifunction display is a 6- by 8-inch (150 mm by 200 mm), high resolution, monochrome active matrix liquid crystal display unit for textual menus and video from the sensors.

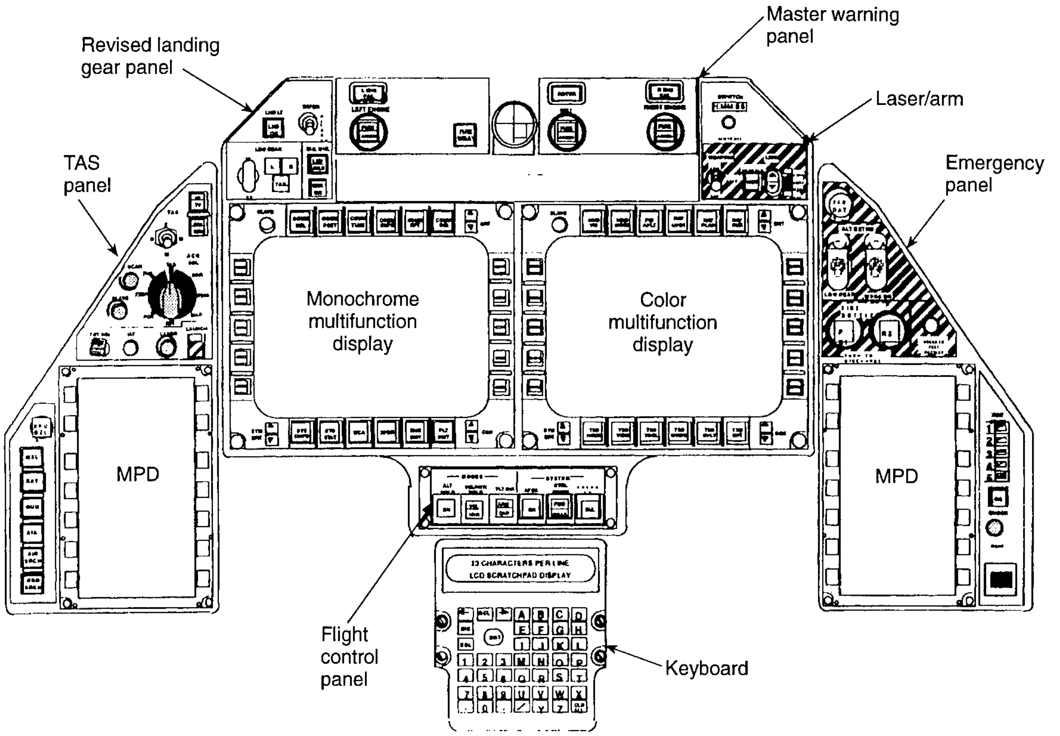


Figure 22. Comanche Cockpit Displays

3.7.2 Navigation and Communication Capabilities

Comanche is the first helicopter to use the joint-service integrated communication, navigation, and identification avionics (ICNIA) system, Figure 23. For navigation, Comanche utilizes an inertial navigation system (INS) and a global positioning system (GPS). The fly-by-wire control system receives aircraft-state variables from the Doppler velocity system and a blade-mounted air data system. A radar altimeter and a digital map interface complete the navigation suite.

For communications, ICNIA provides two single channel ground airborne radio system (SINCGARS) VHF-FM radios, one VHF-AM radio, one UHF-AM HAVE QUICK radio, a MK XII identification friend or foe (IFF) transponder, voice security system, and modern automated data communication hardware, providing three simultaneous transmit (two voice, one data) and five simultaneous receive capabilities.

Comanche digital communications is accomplished through integrated broadcast service (IBS), replacing constant source, improved data modem (IDM) which works with HF/UHF/VHF SINCGARS HAVE QUICK radios and implements four protocols (AFATDS, Air Force, Marine, and MIL STD 188220) and Link-16. Link 16, a waveform and message format of joint tactical information distribution system (JTIDS), is a high-speed digital data and voice communication/navigation/identification single-function supplying position, identification, combat status and targeting information. Link 16 is a proven reliable high-capacity, high-speed "data handler." Link 16 provides the data rate capability for real-time video transmission.

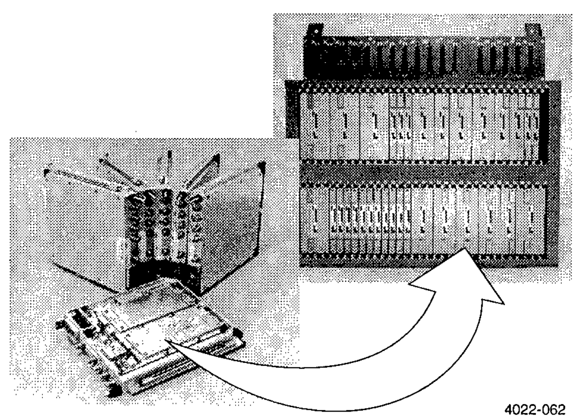


Figure 23. Integrated Communication System

3.8 Weapons and Fire Control

Although small, the Comanche is heavily armed. The Comanche carries a 20 mm, turreted Gatling gun with 500 rounds of ammunition. In addition, the integrated retractable aircraft munitions subsystem (IRAMS) is carried inside internal bays on each side of the aircraft, and has three weapon stations capable of carrying one HELLFIRE or two Stingers, or four 2.75-inch rockets per station. Installation of the external fuel/armament management system (EFAMS) provides an additional four weapon stations per side. These EFAMS stations can each carry the same mix of weapons as the IRAMS does. With the EFAMS installed, the aircraft has a total of 14 weapons stations loadable with any combination of HELLFIREs, Stingers, or rockets. The EFAMS is also capable of carrying external fuel tanks in place of weapons, Figure 24.

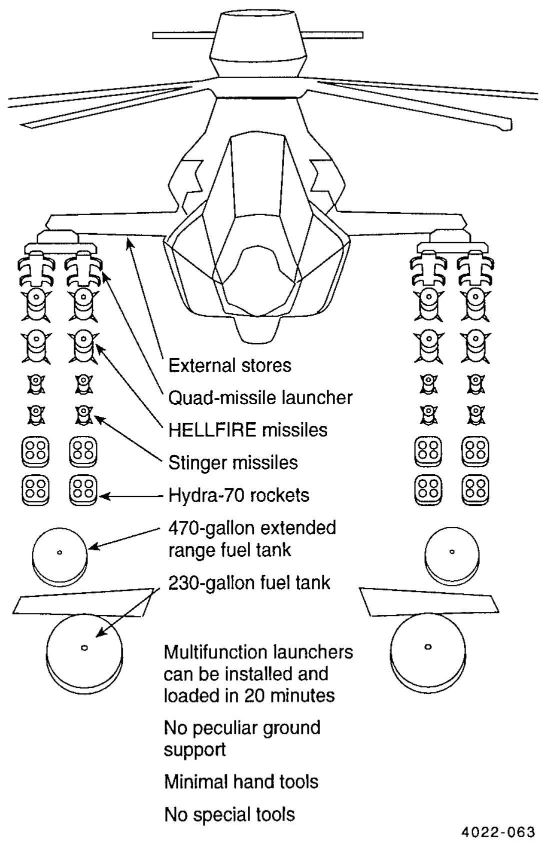


Figure 24. Mission Flexibility

3.8.1 Armament Design Methodology.

The factors that influenced the Comanche armament system design are shown in Figure 25. The demanding environment associated with conducting combat at night (in adverse weather from a helicopter operating NOE) requires that the man-machine interface is fully integrated. During the early Comanche definition phase, the Advanced Rotorcraft Technology Integration (ARTI) program was funded by the Army to identify the required level of automation and advanced crew interface concepts necessary to produce a low workload environment. Rapid prototyping was used to evaluate alternative hardware and software concepts, and the impact each had on both the weapon system performance and the crew. The best candidates were transported to a full-mission simulator for evaluation. The cockpit design, controls and display layout, crew interfaces, flight control interface, sensor interface, and communication/navigation interface was simulated and crews performed combat missions in a combat environment. The most promising approach was then converted to flight hardware and software and flown on the SHADOW aircraft Figure 26. SHADOW made it possible to evaluate the advanced concept in a real flight environment with back-up safety pilots on a standard, proven, production flight controls.

Simulation before design (both hardware and software) has proven to be critical in making timely and cost-effective decisions, Figure 27. Constructive simulation was used to evaluate attributes not easily assessed with flight simulators. Comanche sensor performance and missile loadout requirements are two characteristics established through constructive simulation.

3.8.2 Turreted Gun System (TGS)

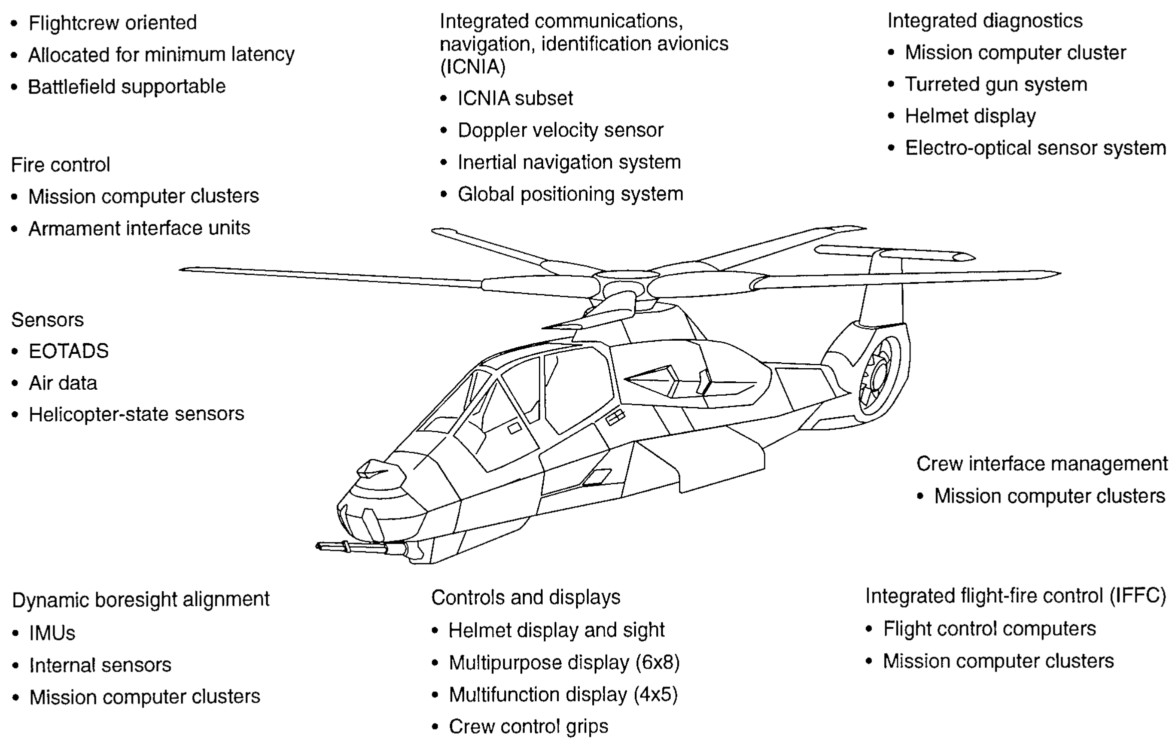
The Comanche TGS is based on the 20 mm gun assembly consists of a high rate-of-fire, three-barrel, Gatling-type lightweight gun; an electric gun drive; and a recoil attenuation assembly, see Figure 28. The gun is capable of firing at rates of either 750 or 1,500 shots per minute, in operator controllable burst lengths of 5 to 270 rounds. The gun drive motor, as well as the ammunition reel drive motor and turret azimuth/elevation drive motors, provide high output power as a result of digitally-controlled brushless motor technology.

The 500 round ammunition feed and storage assembly includes a helical ammunition storage reel, flexibly mounted ammunition feed chuting, an accumulator to compensate for start/stop surges, and a delinker/feeder at the gun interface.

The 20-mm gun selection for Comanche was based on time-of-flight and lethality of the rounds. Comanche's ATA requirement established the need for a high-velocity projectile with a high lethality. A 50-caliber gun did not provide the lethality needed and the 30 mm gun did not provide the projectile velocity required for ATA combat. Guns of the 25-mm size were too heavy.

Location of the gun was a compromise between elevation coverage and blast/flash effects on the nose-mounted targeting and pilotage sensors. Figure 29 shows two candidate options studied for Comanche. The forward location provides 11% ATA combat improvement, relative to the aft configuration. The aft configuration restricted the elevation travel of the gun limiting ATA to directly forward, below, or to the side of the aircraft. Boosting the elevation capability of the aft-mounted gun, lowers the gun, increasing the required landing gear length (increasing weight) and increases drag.

Gun blast pressure influenced the forward location of the gun, as shown in Figure 30. Gun firing tests were used to resolve this issue. Another issue concerning sensor recovery time after, and during, gun firing was also resolved with hardware tests. The Comanche gun is configured to stow aft in the fairing behind the gun turret reducing drag during high-speed operations.



Well-defined functional allocations result in efficient, effective, supportable armament system design.

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Figure 25. Boeing Sikorsky First Team Armament Functional Interfaces

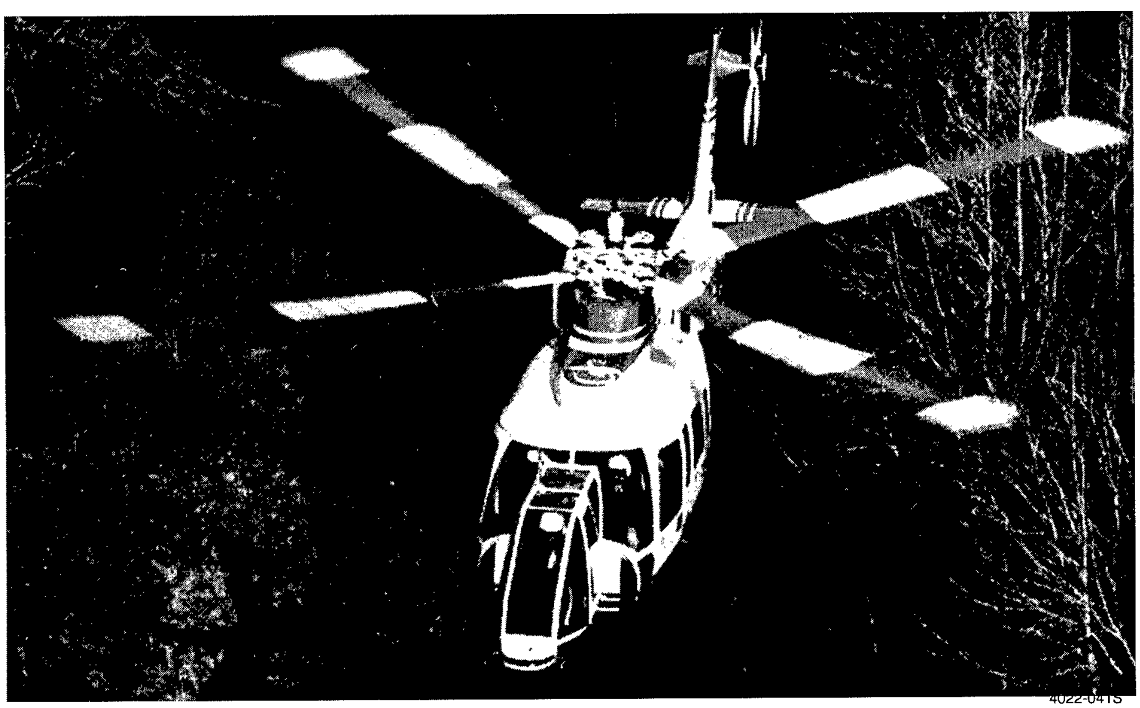

Figure 26. Sikorsky Aircraft Flying Simulator, SHADOW

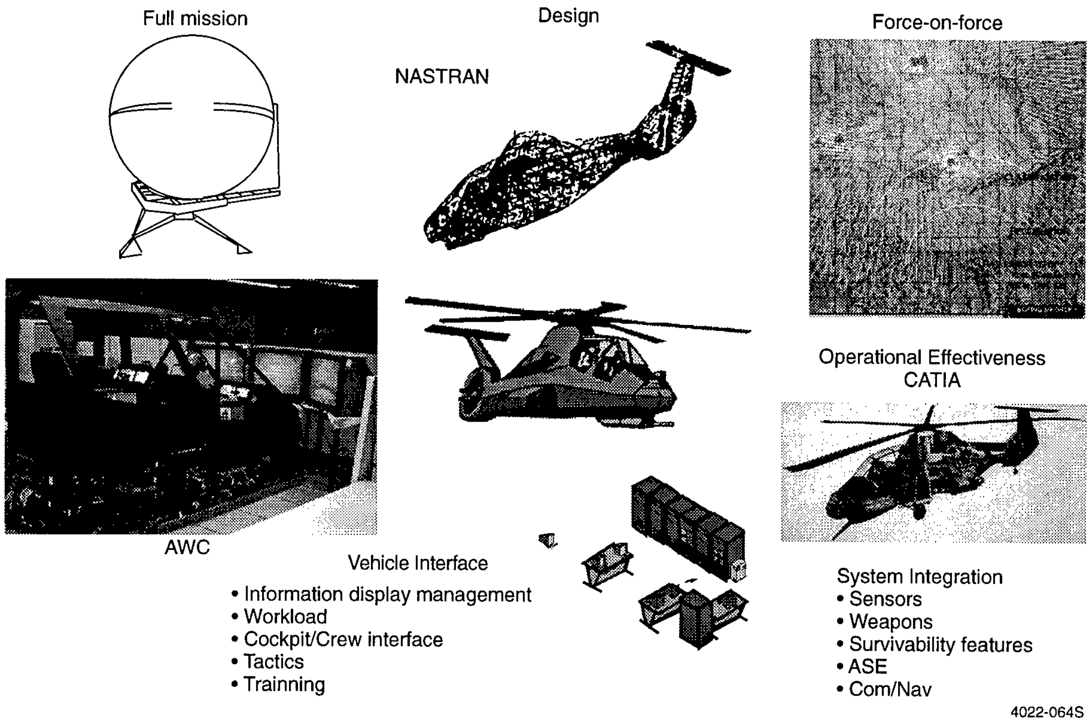

Figure 27. Complex Integrated Optimization Through Simulation

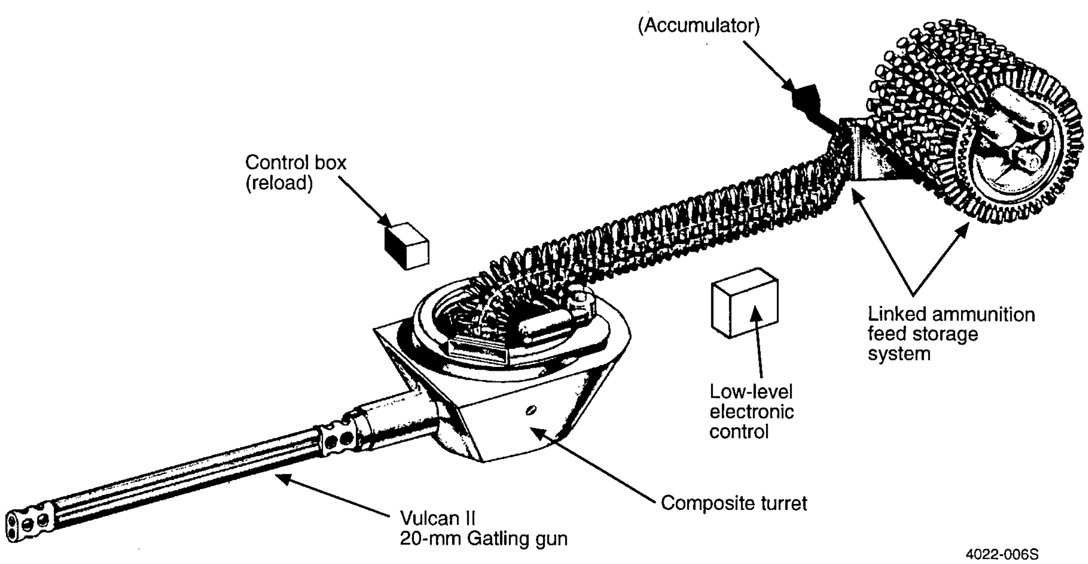

Figure 28. Turreted Gun System (TGS)

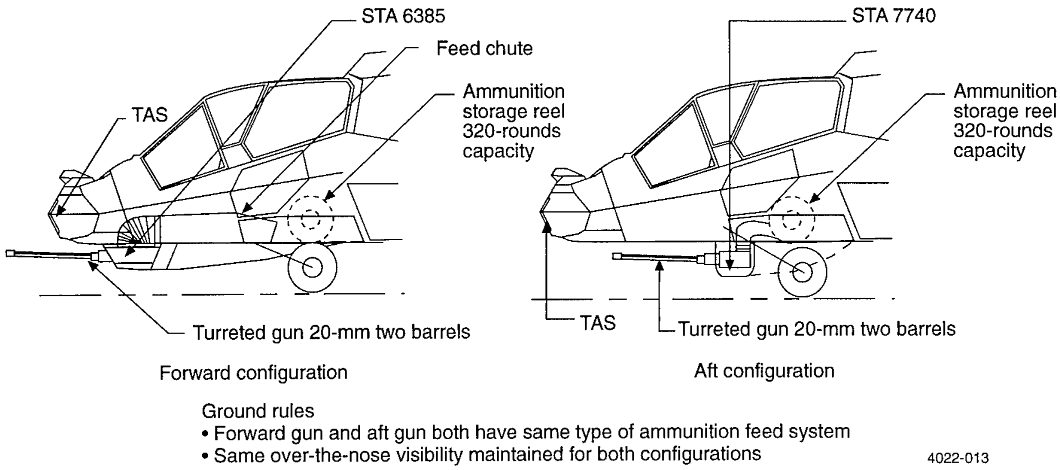

Figure 29. Alternate Configurations

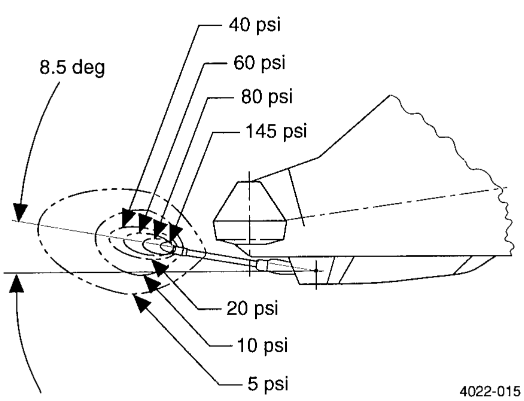

Figure 30. Gun Blast Pressure Profile

3.8.3 Internal Versus External Weapons

Trades were conducted to compare attributes of internal versus external weapons configuration. Configurations used in the trades are shown in Figure 31. It was determined early that the selection of external or internal stores arrangements had a major influence on the basic airframe. Figure 32 shows fuselage differences for internal and external stores configuration. The internal weapons installation lends itself to a primary structure backbone (or central boxbeam arrangement), shown in Figure 33. This permits a modular type construction having vertical parting planes onto which equipment packages (including the weapons bay and MEP equipment) can be mounted. The boxbeam also provides crashworthiness capability preventing plowing during forward crash, and it offers torsional rigidity.

The external weapons arrangement on the other hand, lends itself to a more conventional semimonocoque construction. The external stores support structure attaches to the fuselage via bulkhead or frame-mounted fittings.

It was also recognized early in the design process that an unfaired external stores arrangement would not meet the Comanche LO requirements. The drag of the unfaired external stores configuration also became an issue when the T800 engine power became fixed. The attributes of internal and faired external weapons configuration were thoroughly examined before the retractable internal configuration was selected for Comanche.

The salient weapons trade attributes favoring the internal configuration are shown in Figure 34. Performance improvements accrue to the internal configurations (greater maximum speed, lower system weight), and production cost is based on simplicity of the internal design compared to multiple doors, actuators, and mechanisms needed to enclose weapons in an external wing pod design. Supportability is also benefited where accessibility, reduced complexity, and fewer consumable spares discriminate in favor of internal weapons.

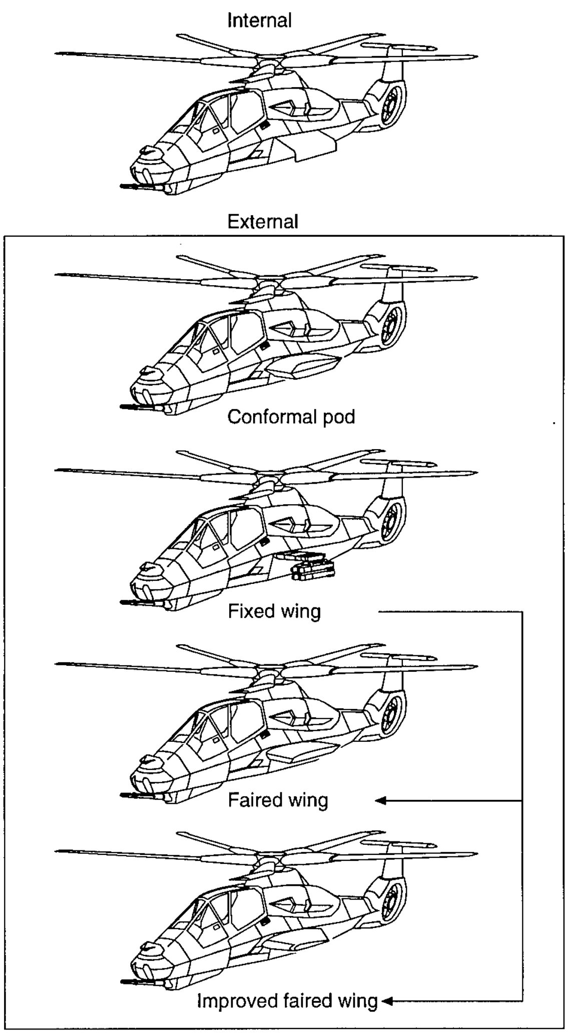

Figure 31. Internal Weapons Proved Superior to Other Configurations Analyzed During Trade Process

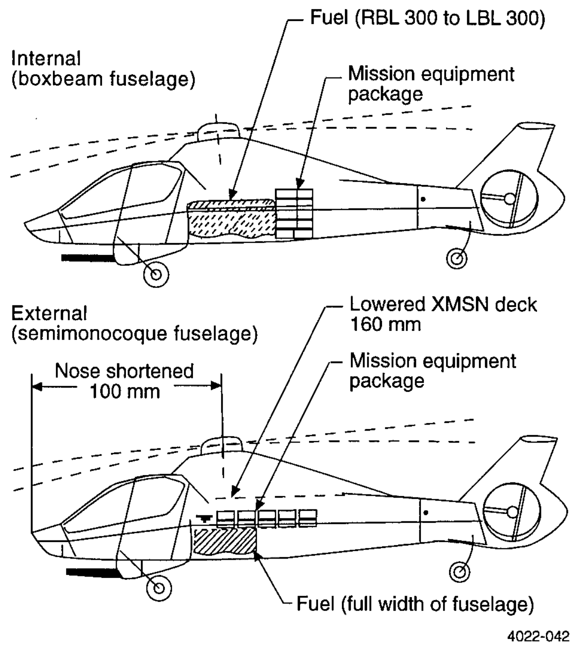

Figure 32. Internal Versus External Stores

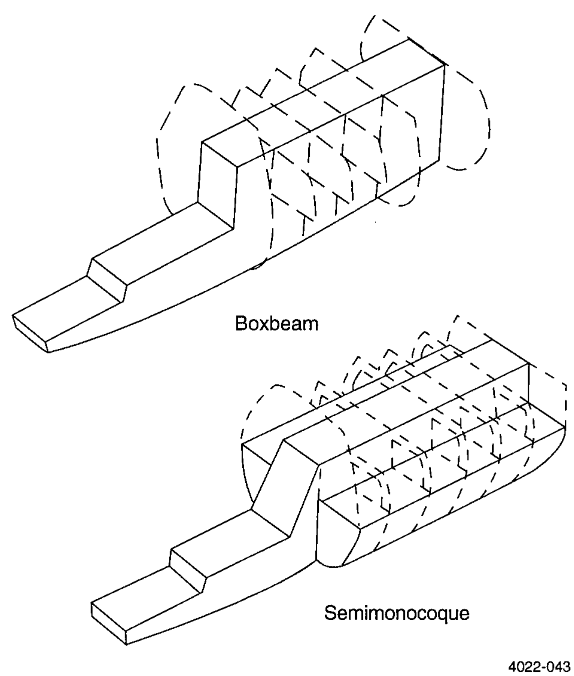

Figure 33. Boxbeam Versus Semimonocoque

	Internal	Faired Wing	Conformal Pod	Improved faired Wing
RCS annex E	Yes	No	No	No
Dash speed Delta kn	–	-18	-15	-12
Weight empty Delta kg	–	+28	+37	+31
Production cost Delta $	–	+$29.6K	+$54k	+$12.5K
Supportability				
• MTBEMA	4.25	4.37	4.23	4.26
• MTBMAF	9.37	9.62	9.43	9.50
• MMH/FH	2.02	2.00	2.05	2.03
• Qualitative	2.00	2.00	3.17	2.49
Consumable spares, Delta $	–	$43.4M	–	–

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Figure 34. Salient Attributes for an Internal Weapons Configuration

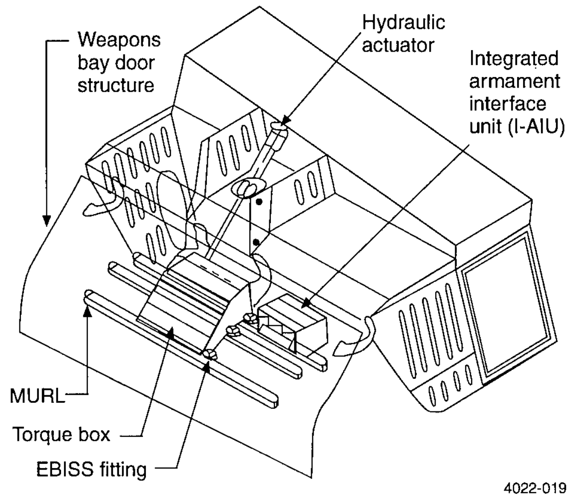

Figure 36. View of IRAMS –Three Missile/Rocket Universal Rails

3.8.4 Integrated Retractable Aircraft Munitions Subsystem (IRAMS)
The IRAMS provides two retractable door assemblies, one on each side of the air vehicle (Figure 35). A cutaway of the left side assembly is shown in Figure 36. Each door assembly mounts three launch rails on a composite torque-beam structure. Each launch rail accommodates either one HELLFIRE one Stinger, or four Hydra-70s, see Figure 37. The IRAMS is designed for maximum weapon lengths of 183 cm, the maximum anticipated for growth weapons (TACANS and LB). However, sufficient volume exists within the bays for potential growth to accommodate weapons up to 200 cm in length. Two degrees of fixed super-elevation with respect to aircraft waterline are provided at each of the six internal stores stations. Missile attitude and rail locations permit satisfactory flight-path clearance to Comanche structure and rotor (in accordance with MIL-STD-1289A) for the normal Comanche flight regime above zero g's (Figure 38).

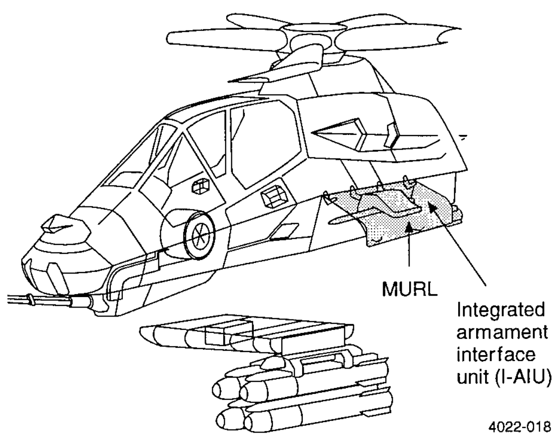

Figure 35. Integrated Retractable Aircraft Munitions Subsystem (IRAMS)

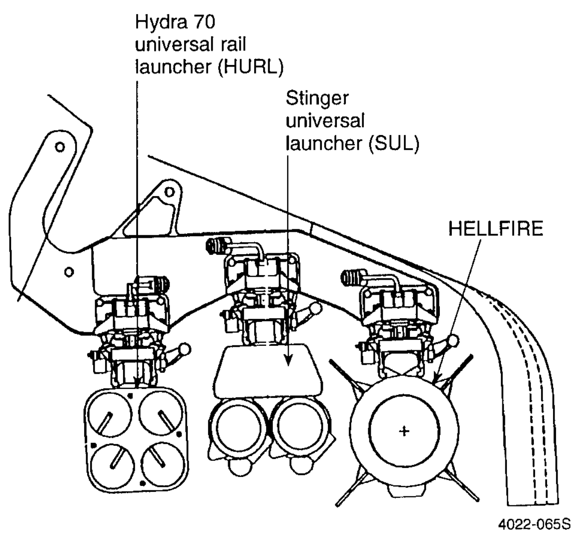

Figure 37. RAH-66 Comanche IRAMS With Mixed Lockout

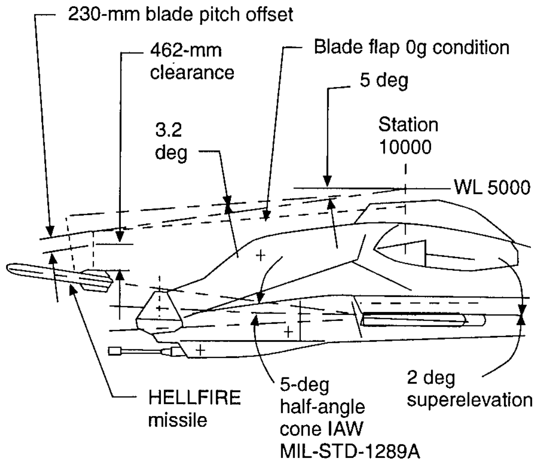

Figure 38. Missile Launch Clearance at 0g Maneuver

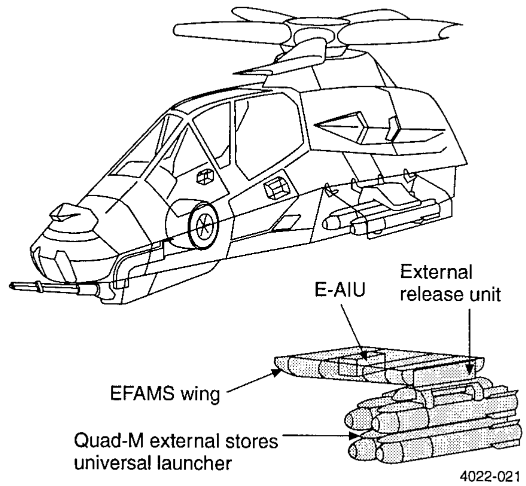

Figure 39. Weapon Loadout Capability Expanded by EFAMS

Fuselage shaping forward of each weapons bay, quickly angling away from weapon flight paths, provide adequate launch clearance with landing gear retracted. Landing gear struts and door arrangement also provide clearance for weapons launch with gear extended. Weapons launch is automatically inhibited during negative g maneuvers and when the aircraft is on the ground.

The IRAMS weapon bays are opened on command within 3 sec. Both bays open simultaneously. Both bays can be opened directly by crew action or as part of the preparation-for-launch sequence as directed by the MEP. The weapon bay hydraulic actuation mechanism enables IRAMS operation throughout the Comanche operational flight envelope (OFE), including sideward flight to 45 kn.

3.8.5 Enhanced Fuel/Armament Management System (EFAMS)
The Comanche is capable of extended range and expanded weapon loadout capability by installation of the EFAMS wings (Figure 39). The wings enable the attachment of two 1890L fuel tanks to provide a 1260-nmi self deployment. Self defense capability is ensured by having internal IRAMS weapon capacity for two Stinger missiles during self deployment.

Through the use of EFAMS, total missile and rocket loadout is more than doubled, maximizing mission effectiveness when required by battlefield events. Weapons loadout with EFAMS installed are shown in Figure 40. EFAMS provides Field Commanders the option to quickly convert from Comanche reconnaissance to a heavy attack configuration.

4.0 AERODYNAMIC TEST
A 1/6th-scale airframe aerodynamic wind tunnel test was conducted in April 1990 at the United Technologies Research Center Large Subsonic Wind Tunnel (LSWT).

The test objectives were as follows:

- Define the total airframe lift, drag, and stability characteristics and the breakdown by component.
- Measure surface static pressures at various inlet and other critical locations.
- Define and correct any sources of aerodynamic deficiencies in the flow quality.
- Evaluate the drag and stability of external stores.

The model was also designed to simulate flight with the retractable weapons bay door opened both with, and without, missiles. The fuselage cavity was simulated for this test with the doors open. The EFAMS extended-range tanks and additional HELLFIRE loadouts were also fabricated and tested.

As shown in Figure 41, opening the weapons bay doors and installing external weapons increases the drag significantly. Opening the weapons bay doors, and installing a four HELLFIRE and two air-to-air Stinger (ATAS) load, increases the drag 8.17 ft2 of which 6.71 ft2 is due to the missiles. Adding the EFAMS pylons, and an additional four HELLFIREs per side results in a total drag penalty of 15.09 ft2. For self-deployment missions, the external fuel tanks combined with the EFAMS pylon increases drag by 5.2 ft2. Dropping the tanks reduces the drag 2.92 ft2.

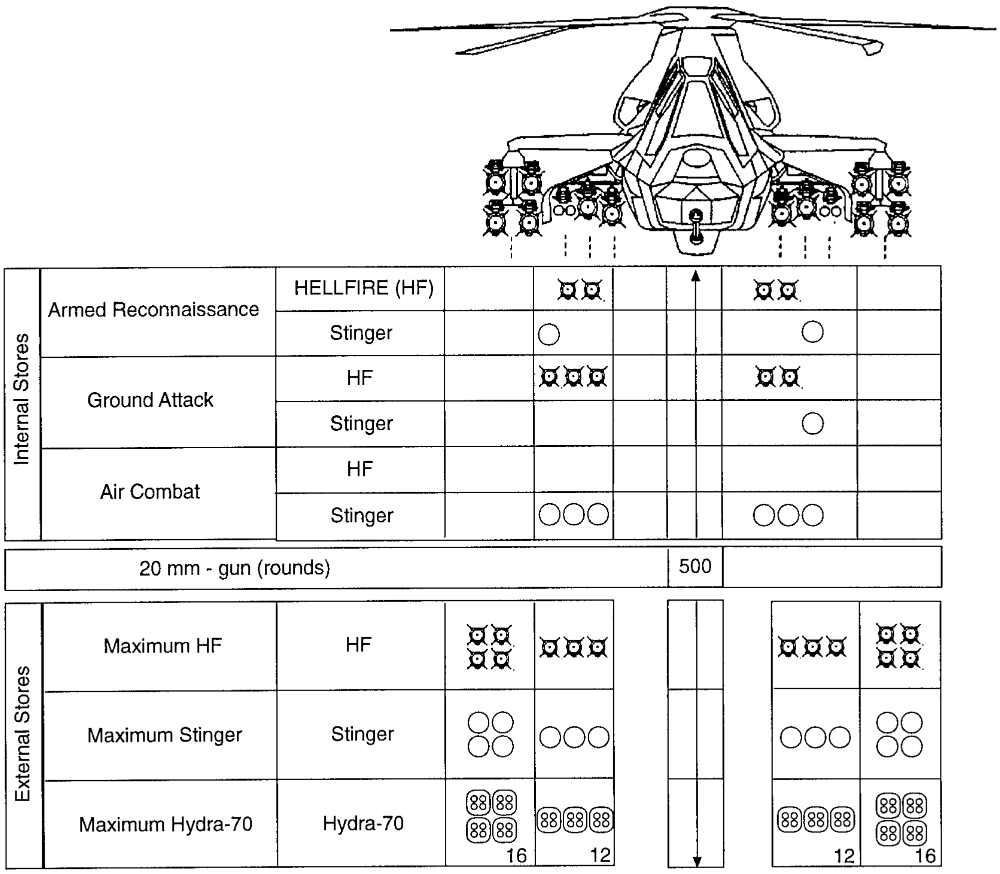

Figure 40. Store Loadout Combinations

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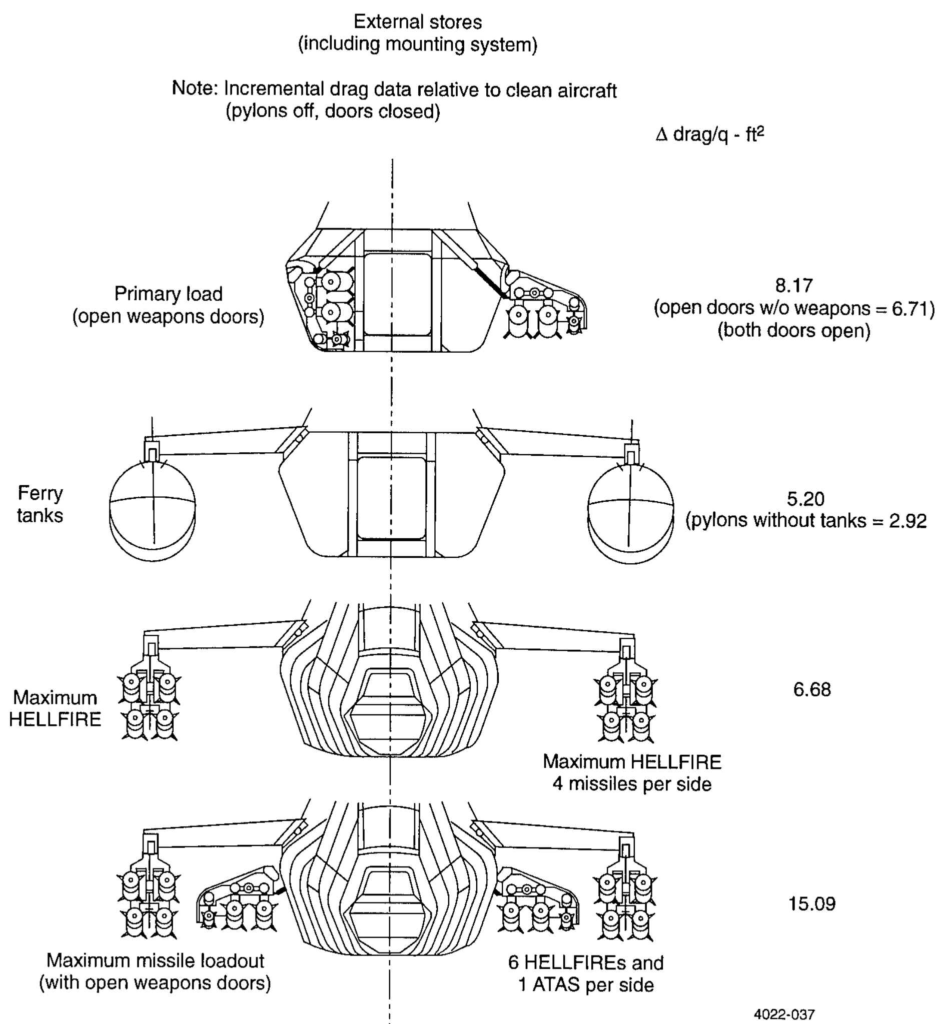

Figure 41. 1/16th-Scale Drag Model External Stores Configurations

5.0 SURVIVABILITY

The Comanche uses radar, acoustic, and IR signature reduction technologies, along with lightweight armor, integrated airborne survivability equipment, and a regenerative nuclear-biological-chemical (NBC) filtration system to maximize its survivability on the future's battlefield (Figure 42).

6.0 SUPPORTABILITY

The most significant supportability aspect of the Comanche is that it is designed to be supported with a two-level maintenance system, Figure 43. The significance relates to the operating and support cost savings realized by eliminating the intermediate-level maintenance resources, to include manpower, facilities, test measurement and diagnostic equipment (TMDE), and other intermediate-level specific support equipment.

6.1 Supportability Design Influence

From the start of the Comanche design, every effort was made to identify and eliminate those design characteristics requiring an intermediate-maintenance level. This process highlighted two significant features that are critical to achieving two-level maintenance:

- **Partitioning:** Need to dissemble expensive subsystems and replace with inexpensive components.
- **Diagnostics:** Need for expensive TMDE to "fault isolate," so that the correct components would be replaced.

Comanche components are partitioned so that parts with different cost and reliability features are segregated for ease in removal and replacement. Diagnostics are incorporated into the design through an integrated architecture so that expensive TMDE is not required. The resulting design philosophy prohibited the layering of com-

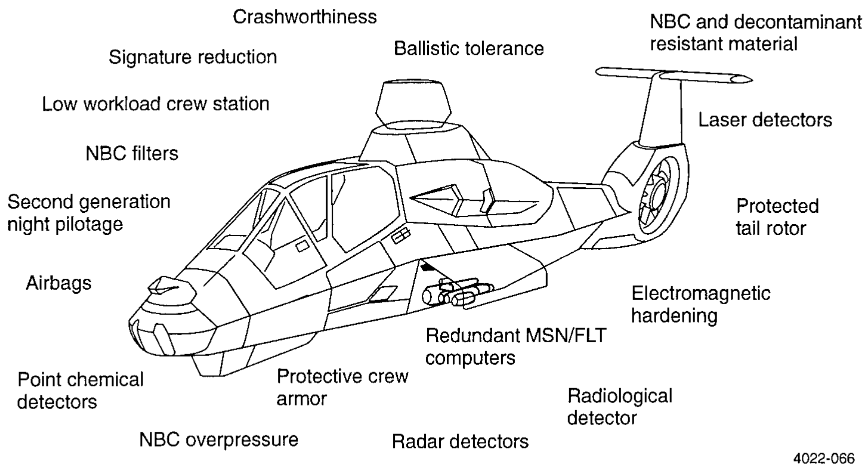

Figure 42. Comanche Survivability Summary

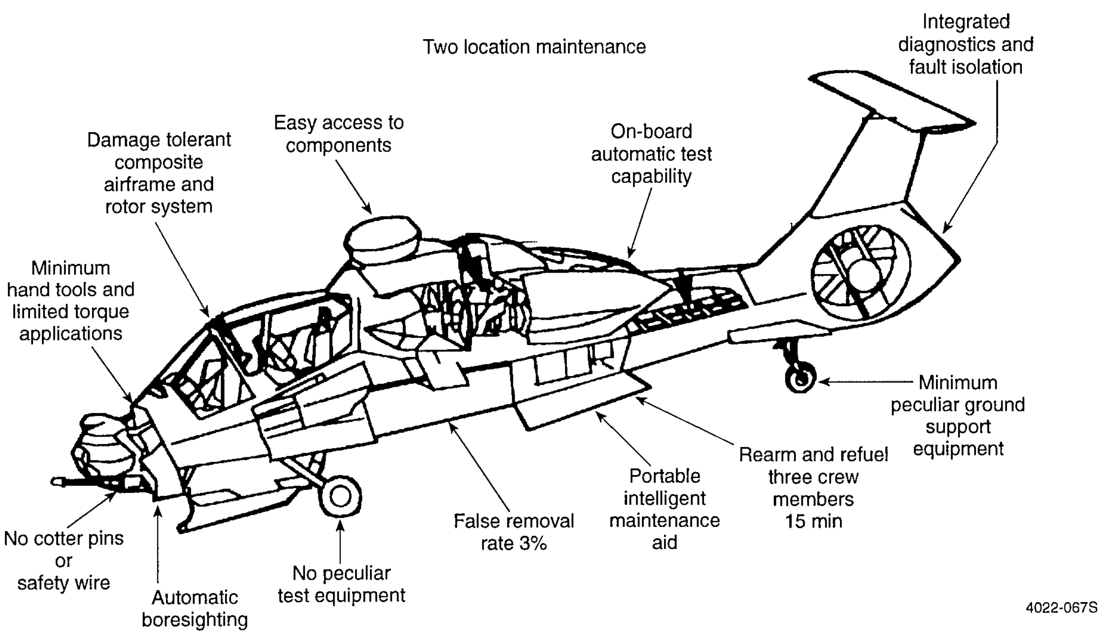

Figure 43. Supportability

ponents, limited the number of fastener sizes used in the design, and emphasized manpower and personnel integration (MANPRINT) features associated with accessibility, anthropometric requirements, and task complexity. This influence was accomplished through:

- Supportability membership in design-related integrated product teams.
- Continuous testability analyses and maintainability assessments.
- Validation of two-level maintenance cost effectiveness through repair-level analysis.

By adhering to this process, intermediate-level tasks were successfully eliminated, and the remaining aviation unit maintenance (AVUM) and depot tasks have been reduced. AVUM tasks comprise remove and replace, on-aircraft repairs, and minor off-aircraft repairs accomplishable next to the aircraft. Depot tasks include component repair in support of the supply system, and major structural airframe repairs and overhaul/rebuild.

6.2 COMANCHE FLIGHT-LINE TOOLS

By incorporating the process outlined above, Comanche requires a flight-line tool box that contains less than 50 tools. Additionally, over 50% of the airframe surface comprise access panels and maintenance platforms. The need for torque wrenches, safety wire, and cotter pins is required by very few applications, significantly less than any other helicopter. Army-validated timeline analysis indicates that the Comanche can be rearmed and refueled in less than 15 minutes.

The Comanche also incorporates a small portable maintenance aid (PMA) which serves as a digital automated logbook and the delivery vehicle for interactive electronic technical manuals. The PMA also acts as an off-board diagnostics aid that interfaces directly with the aircraft's MIL-STD-1553B data bus. All fault data for every subsystem, down to the line-replaceable unit or line-replaceable module level, can be accessed from the data bus.

6.3 COMANCHE VERSUS CURRENT LIGHT HELICOPTER FLEET

The result of this approach has been a revolutionary Comanche design compared to the current light helicopter fleet:

- Manpower needs are reduced by 32%.
- Required maintainer specialties are reduced from nine to four.
- Tools and support equipment are reduced by 83%.
- Number of parts is reduced by 34%.
- Reduced training costs by 50%.
- Reduces maintenance levels from three to two.

As shown in Figure 44, the operating and support costs for Comanche are dramatically lower than any other Army reconnaissance or attack helicopter. The bottom line is that only 25% of the maintenance time for current helicopters is required per Comanche flight hour.

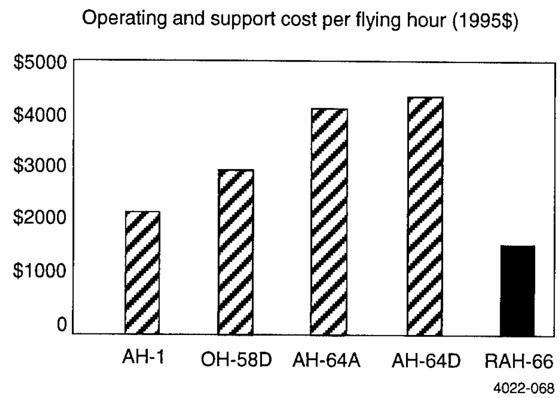

Figure 44. Comanche O&S Costs Are Real and Achievable

7.0 COMANCHE SUMMARY

Comanche is on track to address the reconnaissance role for the Army, and be the attack helicopter of the 21st century. Innovative technologies and design approaches will make Comanche a cost-effective weapon system that will survive on the modern high-tech battlefield.

ACKNOWLEDGMENTS AND REFERENCES

The author borrowed heavily from reference1, an excellent comprehensive description of all the key Comanche technologies. Thanks to Mr. Art Linden and Mr. Marty Stieglitz for their permission and contributions.

Reference 1. Linden, A.W. and Stieglitz, M.H., "RAH-66 Comanche Program Status," presented at AGARD, in 1996.

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SUMMARY

The EH101 is a family of naval, utility and civil helicopters whose design and development have benefitted from the different requirements of each of these operating regimes.

The paper examines weapon integration on the EH101, focussing on the overall weapon system of which the helicopter is a major component. While the details provided are in most instances generic to all naval EH101 variants, specific details of the Royal Navy's Merlin HM Mk.1 helicopter are given where appropriate.

The paper also outlines the highly complex contractual structures that lie behind the Merlin HM Mk.1 programme.

The paper concludes with a number of lessons that should be of advantage to future weapon integration programmes.

LIST OF ACRONYMS

ADS	Active Dipping Sonar
AFCS	Automatic Flight Control System
AHRS	Attitude and Heading Reference System
AMC	Aircraft Management Computer
ASIC	[Lockheed Martin] Aerospace Systems Integration Corporation
ASuW	Anti Surface Warfare
ASW	Anti Submarine Warfare
CCMDU	Cabin Colour Mission Display Unit
CCU	Cockpit/Cabin Control Unit
CDG	Colour Display Unit
CSU	Central Suppression Unit
CWS	Central Warning System
DLP	Data Link Processor
DMS	Digital Map System
DTD	Data Transfer Device
DTI	[UK] Department of Trade and Industry
DVS	Doppler Velocity System
EHI	EH Industries Limited
EIS	Electronic Instrument System
ESM	Electronic Surveillance Measures
FLIR	Forward Looking Infra Red
GPS	Global Positioning System
HADS	Helicopter Air Data System
HC	Helicopter Cargo
HIFR	Helicopter In-Flight Refuelling
HM	Helicopter Maritime
HSIU	Heavy Stores Interface Unit
IFF	Identification Friend or Foe
IRU	Inertial Reference Unit
MASS	Master Armament Safety Switch
MCU	Mission Computer Unit
MMI	Marina Militare Italiana
MoD	Ministry of Defence
MOU	Memorandum of Understanding
MR	Mission Recorder
NATO	North Atlantic Treaty Organisation
PCMDU	Pilots' Colour Mission Display Unit
RDR	Radar
RT	Remote Terminal
SAR	Search And Rescue
SDIU	Sonobuoy Dispenser Interface Unit
SMS	Stores Management System
UK	United Kingdom
USA	United States of America
WPU	Weapon Processor Unit

1. Introduction

EH101 has been a twinkle in the Royal Navy's eyes since the early 1970's when the requirement to replace the Sea King towards the end of the century was foreseen. The resulting programme has drawn in other users and their own requirements. As a result, it is highly complex and has a number of features from which lessons can be drawn for the future.

In describing weapon integration on the EH101, this paper starts by providing a brief history of the origins of the EH101 programme. Relevant portions of the Royal Navy's Staff Requirement for the Merlin variant of aircraft are outlined, followed by a description of the aircraft that has been developed to satisfy that Requirement. A large number of governmental and industrial organisations are involved in the programme; it is necessary to understand the relationships between them if the system integration programme is to make sense. Integration of its weapon systems into the EH101 is then covered. Finally, this paper presents a number of constructive comments that arise from experience with the EH101 Merlin programme.

2. History

2.1 Origins

This programme is a story of partnerships. GKN Westland has manufactured aircraft at Yeovil in Somerset, England since 1915, starting with the licence-manufacture of float planes and progressing onto the development of a large

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number of its own fixed wing designs. In 1948 the company made a strategic decision to specialise in helicopters. Government intervention saw the rationalisation of the British helicopter industry under what was then Westland Aircraft Limited in the late 1950's and the early 1960's. Almost all of GKN Westland's helicopters have been the products of partnerships with other companies, ranging between Sikorsky Aircraft, Eurocopter, McDonnell Douglas and, of course, Agusta. Most of these helicopters have been multi-role and multi-service, usually with naval customers prominently to the fore. As a result, GKN Westland has acquired in-depth experience of the more and less obvious requirements of the naval operating environment that drive the design, manufacture, development and in-service support of maritime helicopters, both in their own right and as part of a larger operating system.

Agusta SpA has a similar long experience of industrial rationalisation, partnerships and the design and manufacture of multi-role helicopters with a strong dash of salt water in their veins.

2.2 GKN Westland/Agusta Partnership

In the 1970's GKN Westland and Agusta were each scheming their own conceptual designs for a new generation medium lift helicopter to replace the Sea Kings and ASH-3s in service with respectively, the British and the Italian armed services. A Memorandum of Understanding was signed in 1979 between the Italian and British governments to cooperate in the joint development of such a helicopter, to fulfil the naval roles of Anti Submarine Warfare (ASW) and Anti Surface Warfare (ASuW). The Memorandum of Understanding also included tactical utility and civil variants of the helicopter, to reap the benefits of commonality of airframe and systems and to expand the market base (Figure 1).

Agusta and GKN Westland formed a 50% / 50% joint holding company based in London to manage the development, production and support of the EH101 helicopter. EH Industries Limited (EHI) allocates work between the two companies on an equal basis, interfaces with contractual customers and is responsible for the promotion of the helicopter to potential customers (Figure 2).

The three distinct, but very closely related, variants of the EH101 involve design, development and certification challenges that have been, perhaps, the major feature of the programme, especially when they have had to satisfy the requirements of the armed forces of two countries (UK and Italy) and the civil certification authorities in three (UK, Italy and USA). The complexity of this situation has had its benefits in that it has not only highlighted the commonalities between the military and civil requirements but forced the programme to profit from those commonalities in order to achieve a coherent overall programme.

2.3 Merlin

The British Royal Navy's Merlin Helicopter Maritime (HM) Mk.1 is the first EH101 variant to be delivered to its customer, but is not just a helicopter. It is to replace the Royal Navy's Sea King helicopters and some of its Navy Lynxs, but is to expand the capabilities offered by both of these aircraft. For too long aircraft have been regarded, depending on the viewer's outlook, as either an airframe or a collection of black boxes flying in close formation, without recognising that what really interests the operator is how well the overall mission can be performed given, and sometimes despite, the characteristics of the equipment to hand. The airframe and its contents are themselves almost incidental to the overall performance of the whole system. Industry now recognises this, as does the British Ministry of Defence (MoD), who ran a competitive tender competition for the prime contractorship of the overall EH101 Merlin system programme. Their extensive experience of the successful fulfilment of a comparable role in the US Navy's LAMPS III programme was one of the more significant of many factors that lead to the award of this contract to IBM Federal Systems. Thanks to a bewildering succession of rationalisations of the defence industry, the EH101 Merlin prime contractor is now Lockheed Martin Aerospace Systems Integration Corporation (Lockheed Martin ASIC). The relationships between Lockheed Martin ASIC, EHI, GKN Westland and Agusta will be described in more detail later. As just stated, Lockheed Martin ASIC is the prime contractor responsible for the integration, performance and delivery of the complete weapon system of 44 Merlin HM Mk.1s (and developments thereof) for the Royal Navy, to specification and on time. EHI is its prime subcontractor.

EHI is prime contractor for all other EH101 contracts, although in certain special cases other arrangements may apply: the prime contractor for the British Royal Air Force's 22 Merlin Helicopter Cargo (HC) Mk.3s, which are based on the EH101's utility variant is GKN Westland, with EHI as the principal subcontractor and thereon as normal. Similarly, Agusta is the prime contractor for the forthcoming order from the Italian Navy (Marina Militare Italiana, or MMI) for up to 16 EH101s made up of naval, tactical utility and search and rescue variants. EHI is pursuing actively other military and civil customers.

3. Operational Requirements

To avoid confusion between the concepts and practices of navies that operate worldwide but whose operations are based in the very different operating environments of the North Atlantic and the Mediterranean, discussion of the formal naval operational requirements for the EH101's initial customers are best focussed onto one particular variant. The Merlin HM Mk.1 for the Royal Navy has been chosen here, while passing references are made to MMI

requirements. However the Royal Navy's Staff Requirements and the resulting performance and characteristics of the Merlin HM Mk.1 cannot be discussed in any meaningful way without straying almost immediately into classified domains. The following information on EH101 aircraft and system features therefore relates (unless otherwise stated) to a generic EH101 naval variant, whose semblance or otherwise to any given operator's variant, and whose compliance with any given operator's requirements, must be left to the reader's own conjecture.

In its original Staff Requirements, the Royal Navy specified some key aircraft performance markers for Merlin, as part of the specified performance of the overall system (Figure 3). The first two are speed and endurance to allow operations at extended ranges and to permit quick reaction to, and attack of, submarine targets. EH101 can carry up to four lightweight torpedoes or depth charges. Its typical speeds are: dash at up to 150 knots; economical cruise at up to 140 knots on three engines; or else loiter (for maximum endurance) at up to 120 knots on two engines, providing some three hours on station searching well ahead of the fleet.

The third feature is an integrated mission system which can process data from a comprehensive suite of sensors. This gives EH101 an independent capability to search for, locate and attack targets. Independent (or autonomous) operation means having no need to call on the support of another unit to detect, classify or prosecute an evading, fast, quiet submarine.

Versatility was a fourth key requirement, to enable the helicopter to carry out a wide variety of roles and to respond quickly to emergency tasking flash points around the world.

Agility was the final characteristic. EH101 is necessarily a substantial helicopter (Figure 4) in order to accommodate its intended capabilities, but it possesses sufficient power, manoeuvrability and control margins to allow safe operations from frigate-sized flight decks in demanding weather conditions, day and night. Although half as heavy again as the Sea King, the footprints of the two aircraft are not that different. EH101 will launch and recover typically in Sea State 6 in up to 35 knot crosswinds, to allow its mother ship to continue to monitor her towed array sonar without the need to alter course into wind. Once over the deck, the helicopter is made fast by engaging a rapid securing harpoon device in a grid on the deck, while the rotor system can generate negative thrust if necessary. The harpoon is integrated into a semi-automatic handling system for aircraft handling and weapon loading.

The weapon system that comprises Merlin HM Mk.1 and the Type 23 frigates on which it will be based initially has been designed to provide maximum operational efficiency by the use of advanced technology (Figure 5) to reduce crew workload while maintaining a very high state of readiness and aircraft availability. Coupled with these attributes, the Royal Navy's reduced manning philosophy has driven the EH101 towards operation by three aircrew: a single pilot and two mission operators in the cabin. The aircraft is fully capable of being flown solo. Its handling qualities are excellent throughout the flight envelope. The autopilot modes permit hands-off flight for most of the mission, and systems are in some cases triple redundant with benign failure modes. With three engines, a single engine failure will not be flight critical in 95% of cases, allowing the pilot to resolve the emergency in slow time and to recover safely to base. The only problem may be with crew availability: the aircraft will still be ready to fly when the single pilot, observer and sonics operator have run out of duty time and are tucked up in bed. For wartime operations the concept is invaluable, since ships' flights can be double manned in times of conflict with only six aircrew. In peacetime, novice pilots will train and gain experience in a larger carrier-based squadron first with the left hand seat invariably occupied by a senior aircraft captain to maximise instructional value. The observer and sonics operator face aft to keep the size of the environmentally controlled cockpit and cabin booth area to a minimum (Figure 6). Mission planning and debriefing are made easy by use of a data collation device while a solid state Data Transfer Device is used to load and download operational engineering information.

4. Missions

4.1 Primary Missions

The Primary Missions of Merlin are active and passive Anti Submarine Warfare and Anti Surface Warfare. In the ASW role, Merlin will have a simultaneous active and passive sonar capability. The Ferranti Thomson FLASH medium / low frequency sonar will be a major advance, giving enhanced detection ranges with the ability to search below the layer at depths of about 2000ft. Passive sonar is centred on the GEC AQS903 sonics processor. The capability of EH101 to auto-time share sonobuoys will be double that of the Sea King, while the mission computer will process tactical data to achieve an attack solution.

Its autonomous capability is the feature that makes EH101 unique among ASW helicopters. Based on its own information, or on initial contact data passed on from another unit, EH101 will be able to locate, identify and attack without assistance. It is this that will give the Command the edge when conducting ASW operations at long range from the main body of ships.

In Anti Surface Warfare, Merlin's surveillance capability is provided by the GEC Marconi Avionics Blue Kestrel radar and the Orange Reaper Electronic Surveillance Measures (ESM) systems, which will be able to intercept and analyse in excess of 500 radars. In a four-hour sortie, using radar and ESM, EH101 will be able to search over an area approximately the size of mainland Great Britain. It will datalink to other units a comprehensive surface picture

enabling targets to be engaged with surface-to-surface or air-to-surface guided weapons. The Royal Navy's Merlin will not have an ASuW missile system initially, but it is planned to install and integrate one later in service. The MMI EH101's ASuW tasking, which could differ in several respects from that of the Royal Navy, is planned to be met by equipping their EH101s with the Alenia Difesa Marte Mk.2 medium range missile system that has been proven on their ASH-3 Sea King helicopters.

4.2 Secondary Missions

The Merlin's main Secondary Missions are Search and Rescue (SAR), Casualty Evacuation, Troop Transport and Vertical Replenishment / Cargo Lifting. The versatility to carry out such a wide variety of secondary roles is derived from flight performance and the available payload - in other words, versatility favours a large, powerful and adaptable helicopter such as the EH101.

EH101's voluminous 28 cu metre cabin gives it the ability to carry eight stretchers, medical attendants and full medical equipment.

In the amphibious commando support role, EH101 can carry 12 troops with the full ASW mission system fitted, and 20 with a partial strip comprising removal in 30 minutes of the sonar and the two sonobuoy dispensers. When the mission system is fully removed the cabin can accommodate up to 30 fully equipped troops.

In the vertical replenishment role, EH101 can lift 4500kg of underslung cargo, while the wide cabin doorway permits the internal loading of standard NATO pallets.

The Search and Rescue mission will use the same surveillance systems as are employed in the primary roles. Worldwide digital map data will be loaded into the mission computers via the Data Transfer Device. The integrated satellite navigation system, combined with the Inertial Reference Unit and the Aircraft Heading and Attitude Reference System, will provide exceptionally accurate navigation which, along the Doppler, Radar Altimeter, preplanned SAR search patterns and hands-off automatic transitions, will fly the helicopter into the hover, in the right spot, in the shortest possible time. Auxiliary hover control by the winchman will then ensure a swift rescue, using the hydraulically powered hoist positioned above the cargo doorway.

The aircraft's range and endurance can be extended by carrying out Hover In Flight Refuelling (HIFR) from any suitably equipped ship; a dedicated HIFR point is located internally in the cabin, just aft of the cargo doorway.

Although not specified for the Royal Navy's Merlin HM Mk.1, other EH101 variants for which SAR is of higher priority are equipped with facilities such as a Forward Looking Infra Red (FLIR) sensor and in-flight refuelling facilities. Like other aircraft that have adopted the multiple variant design approach, EH101 facilitates compilation of equipment drawn from several programmes into a new-build variant specific to a given operator; this benefit also applies to retrofit programmes.

5. Mission Systems

5.1 Integration

The avionics systems on board the EH101 are designed on a federated basis (Figure 7), focussed on overall control through the Aircraft Management System. By this means, full integration of aircraft systems is achieved, providing processing and management of navigation and sensor data and exchange of that data back and forth with the mission system.

Looking at the aircraft management and mission systems in more detail (Figure 8), and with no apologies for the alphabet soup that is inevitable in an architecture of this complexity, some top level features are as follows:

- two MIL-STD 1553B databases, one for the aircraft management system and one for the mission system. This is to ensure ample spare capacity for future expansion in both areas and to provide low data latency.
- serial connections using ARINC 429 links, in instances in which rapid data transfers are crucial.

Perhaps the mission avionics is more comprehensible in the form of Figure 9, which concentrates on the key elements. Although other crewmembers have ready access to mission data, the prime coordinator is the observer, seated at the mission console in the cabin.

5.2 Store Management

The Stores Management System (SMS) provides the capability to select, preset, arm, selective jettison, emergency jettison and release stores carried by the helicopter. It provides the airbreaks that are necessary for critical functions.

The principal concern behind the EH101's SMS is that it should operate safely. The SMS design reflects the wariness still exhibited by the UK aircraft armament regulations towards software control. The SMS safety requirements, listed below, can only be implemented at the initial design stage.

For store release:

- No single fault shall prevent the release of a store when intended except where imposed by external simplex release equipment;
- No single fault shall result in the inadvertent release of a store.

For selective and emergency jettison:

- No single fault shall prevent store jettison when intended except (for internal, non-armament stores only) where imposed by external simplex release equipment;
- No single fault shall cause unintended store jettison.
- No single fault shall cause jettisoned stores to be live when selected safe (normal) or safe when selected live.

For the store arming function:

- No single failure shall prevent a weapon from being released in the correct arming state when required except where imposed by external simplex release and/or arming equipment;
- No single fault shall cause the inadvertent arming of a store;
- No single fault shall prevent a store from being made safe after having been made live.

Figure 10 provides an overview of the SMS architecture, which implements the SMS functions just described. The SMS' component parts include:

5.2.1 Weapon Processor Unit

The Weapon Processor Unit (WPU) interfaces with the Mission Computer Unit (MCU) via the Mission databus. Because of safety considerations, discrete controls are provided so that the crew can exercise overall control of the system:

- Master Armament Safety Switch (MASS), located in the cockpit, enables the armament DC supplies. A remote indicator displays MASS status to groundcrew;
- Late Arm Switch (mission console pilot's and co-pilot's cyclic sticks);
- Release Switch (mission console, pilot's and co-pilot's cyclic sticks);
- Selective Jettison Guard Switch (mission console);
- Selective Jettison Switch (mission console);
- Emergency Jettison Switch (pilot's and co-pilot's collective sticks).

The WPU has a duplex structure to meet the safety requirements. Duplex hard wired switching is provided to ensure that there are at least two airbreaks in safety related circuits. Each half of the WPU has a separate remote terminal (RT), however both RTs use the same address. Management of the two RTs is therefore confined to the WPU.

5.2.2 Heavy Stores Interface Unit

The two Heavy Stores Interface Units (HSIU) provide the electrical interface between the WPU and the stores' and heavy stores' carriers. Each heavy store carrier includes an Electro Magnetic Release Unit, which performs the actual release and jettison functions although, for torpedoes, a Release Unit Adaptor (RUA) is used to interface the torpedo physically to the aircraft. This is described in more detail below.

5.2.3 Sonobuoy Dispenser Interface Unit

The Sonobuoy Dispenser Interface Unit (SDIU) provides the electrical interface to the two 'carousel' type sonobuoy dispensers. Each dispenser can hold up to 10 sonobuoys, any one of which can be positioned for release, thus enabling the immediate selection of any two out of 20 buoys. The dispensers may be refilled from sonobuoy racks within the cabin.

6. Armament Specifics

As noted already, the EH101 has the ability to carry up to four lightweight torpedoes or depth charges, as well as a number of sonobuoys and light stores. While it is not possible to comment in this paper on Merlin's capabilities in this respect, it is worth taking a brief look at two special aspects of the heavy store carriage method particular to Merlin within the EH101 family.

Most, if not all, British armed frontline aircraft carry their external stores using the saddle lug suspension method, sometimes known as MACE (Minimum Area Crutchless Equipment). Unlike the bail lug suspension method, whereby the store is suspended via two annular lugs and lateral movement is prevented by swaybraces, the saddle lug method requires all store loads to be reacted back into the aircraft via the suspension lugs themselves. The benefit, at least for fixed wing aircraft, is that the weapon pylon's parasitic aerodynamic drag and radar signature are greatly reduced; store turnaround times can also be significantly less.

The drawback is that reaction loads between the store and aircraft are more severe, requiring a more robust (and therefore heavier) weapon pylon. It is likely that all non-British maritime EH101s, unless specifically required to the contrary, will use the bail lug suspension method.

The suspension bands used to suspend torpedoes from British aircraft have saddle lugs built in. These suspension bands, like the conventional suspension bands used in all other torpedo installations, separate from the torpedo following its release but before it enters the water, and are not recovered. The cost of these suspension bands is not inconsiderable, and the British armed forces are moving towards the adoption of a Release Unit Adaptor (RUA) (Figure 11) that interfaces with the aircraft's weapon in a similar way to a pair of MACE suspension bands; when the torpedo is released, a pyrotechnic cartridge unlatches a lock mechanism, suspension arms around the torpedo open, and the torpedo falls away in the normal manner. The RUA remains on the aircraft, and its arms are folded by hydraulic damper units. The RUA may be reused after simple refurbishment. In the unusual event of torpedo jettison, as opposed to release, the weapon pylon's release unit provides the release function; the torpedo falls away complete with the RUA.

7. Integration Programme

The integration of Merlin's weapons with the remainder of the aircraft has had to take into account the double-headed nature of the EH101 programme: the EH101 aircraft with its core avionics and other existing basic and naval variant features, for which EHI is responsible; and the aspects of Merlin that are unique (at least so far) to this particular aircraft for which, as part of the whole Merlin programme, Lockheed Martin ASIC is the prime contractor.

Figure 12 details the workshare between Lockheed Martin ASIC and EHI, but reflects the fact that in practice, for the Merlin programme, GKN Westland is taking the lead on behalf of EHI.

So far as weapon integration is concerned, most of the systems involved already form part of the baseline EH101, although they need to be interfaced with UK-specific equipment such as the radar and sonics.

Figure 13 reveals a fairly conventional integration programme. Flight trials have reached the stage by which torpedo release trials are due to take place very soon.

8. Programme Milestones

The Merlin introduction into service has slipped due to specification changes and delays in both funding and development. However the programme is now on track, with the delivery of the first production aircraft, RN01, achieved in 1996, and the first flight in January 1997 of RN02 equipped with the aircraft's full mission system. The In-Service Date is in 1998, and the first aircraft is due to be flying operationally at sea in 2000.

9. Training

The continuing operational effectiveness of Merlin will be very dependent on high quality training, in preparation for entry into service and thereafter. With the pressures on ship, submarine and aircraft programmes making it more and more difficult to conduct training in the real environment, the need for quality, high fidelity training systems is clear. Merlin's integrated training system will cater for all aircrew and maintainer training needs.

The various elements are:

- Cockpit Dynamic Simulator
- Cockpit Procedural Trainer
- Three Rear Crew Trainers
- Common Control Unit and Tactical Display Part-Task Trainers
- Weapon Systems Trainer
- Mechanical Systems Trainer
- Engine Change Unit Trainer
- Computer Based Training
- Computer Assisted Training Courses
- Dedicated, purpose-built infrastructure

10. Lessons

Experience is only worthwhile if lessons can be drawn from it; it is negligent not to draw on those lessons that are available.

The EH101 weapon integration programme passes both these tests, in that constructive lessons can be drawn. A litany of successes achieved would be repetitious and self-congratulatory, so the following lessons may court minor controversy by cataloguing some instances in which, with the 20:20 vision of hindsight, and to adapt the Irish expression, "we shouldn't have started from here". These lessons have already been absorbed and implemented by the EH101 programme.

10.1 Upscoping / Downscoping of Specifications

Specifications for modern avionic systems require the provision of spare capacity, often 50%, to cater for the inevitable upgrades and modifications that occur through the equipment's life in service. By coincidence, the EH101 programme has spanned the change in world events that has had the most monumental effect on worldwide defence planning since the Second World War: the end of the Cold War. This has lead to a radical reappraisal of defence priorities. As a direct result, on the EH101 programme as on others, some system capabilities have had to be increased while the requirement for others has reduced or even withered away. Spare capacity must be provided to allow expansion, but the constructive lesson to be learned

is that the system should also be flexible enough to shrink when necessary, without leaving unprofitably employed capacity.

10.2 Avionics Obsolescence

The EH101 programme has been a lengthy one, for many valid reasons. Perhaps the most obvious is that the development of a complete new aircraft and its systems does not happen overnight. Programme managers must take into account the rapid evolution of technology, and consider whether systems selected for installation on board the aircraft when the programme was launched should not undergo a mid life update to ensure that the aircraft enters service with current technology.

10.3 Value for Money

Providing the operator with value for money has always been good business practice, but now has a higher profile than before in the eyes of procurement agencies. Mention will be made here of only two of the many aspects of this topic.

10.3.1 Contractor Hierarchy

There can be a tendency in programmes-led contracts for the technical specialists in individual, specific areas within the aircraft and system subcontractors to be separated by a contractor hierarchy that unwittingly hinders or even blocks communication. There is a special danger of this when communication must pass through intermediate layers that do not appreciate, for example, the importance attached to unique, obligatory design or certification requirements of an individual customer. Programme managers should take these factors into account at the initial stages of workshare allocation, by constructing contractor hierarchies that allow short lines of communication. This should prevent the highly undesirable temptation to resolve technical problems via unofficial back-door contacts.

10.3.2 Concurrent Design

The EH101 programme has embraced the concept of concurrent design, whereby all the design specialisations are involved simultaneously rather than consecutively. The quality of the design improves markedly, response time to the customer falls, and the operator's need is satisfied more swiftly and cheaply.

10.4 Design Authority

Allusion has already been made to the 50%/50% work share split between GKN Westland and Agusta. This extends to allocation of Design Authority. This has not proved to be ideal, but neither would a 51%/49% split. Further thought needs to be given to how to share responsibilities for a programme while retaining equal partnership.

11. Conclusions

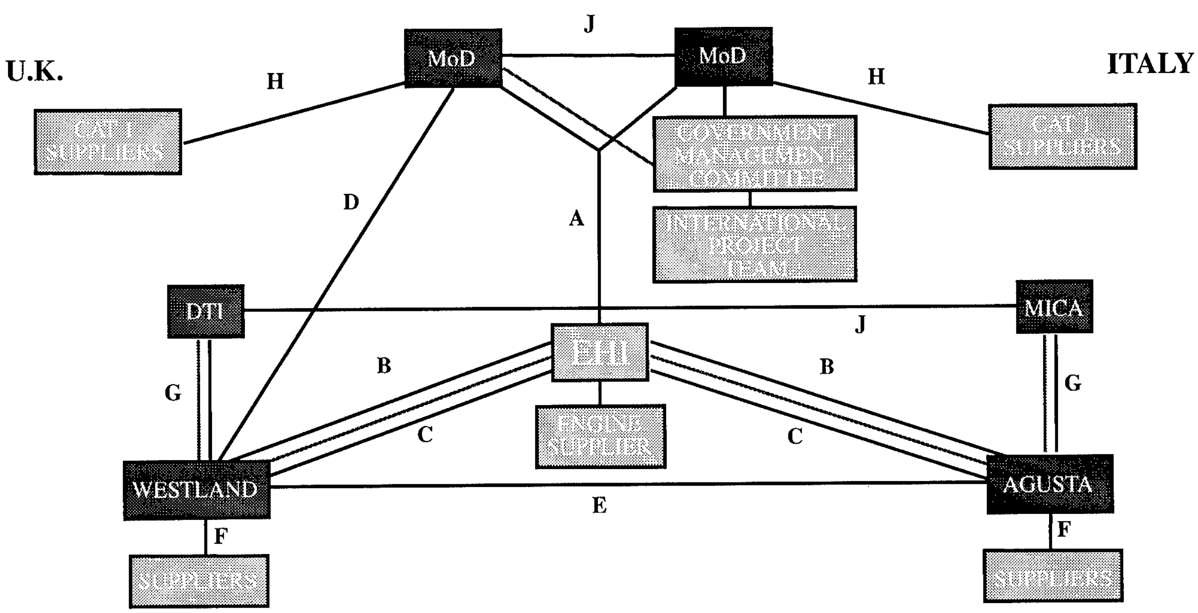
There is no doubt that EH101 will be a most effective multi-role maritime weapon system. This paper has recognised the programme's design philosophy by addressing weapon integration on a broad front, and not by concentrating on the weapon: aircraft interfaces. EH101's ability independently to carry out its primary roles and to remain on station for long periods far from shore or ship are its pre-eminent capabilities. There is no other aircraft in existence today or planned for the future that is capable of meeting the operational needs of the Royal Navy and other operators into the next century.

Acknowledgements

The author wishes to express his gratitude to those colleagues in GKN Westland and Lockheed Martin ASIC who have contributed towards the preparation of this paper.

- Integrated design, development and production of 3 basic variants
  - Utility/SAR
  - Civil/VIP
  - Naval

Figure 1 **THE EH101 FAMILY - A NEW CONCEPT**



KEY
- A Main Development Contract
- B Main MoD Development Sub-Contract
- C Commercial Development/ Productionisation Sub-Contract
- D Associated Agreement
- E Inter-Company Agreement
- F Supplies for Development Programme
- G Launch Aid/Equivalent
- H Category 1 Supplies
- I Engine Supply Contract
- J Inter Government MOU

Figure 2 **EH101 MANAGEMENT /CONTRACT STRUCTURE**

- Speed
- Endurance
- Integrated mission system
- Versatility
- Agility

Figure 3 **MERLIN KEY PERFORMANCE MARKERS**

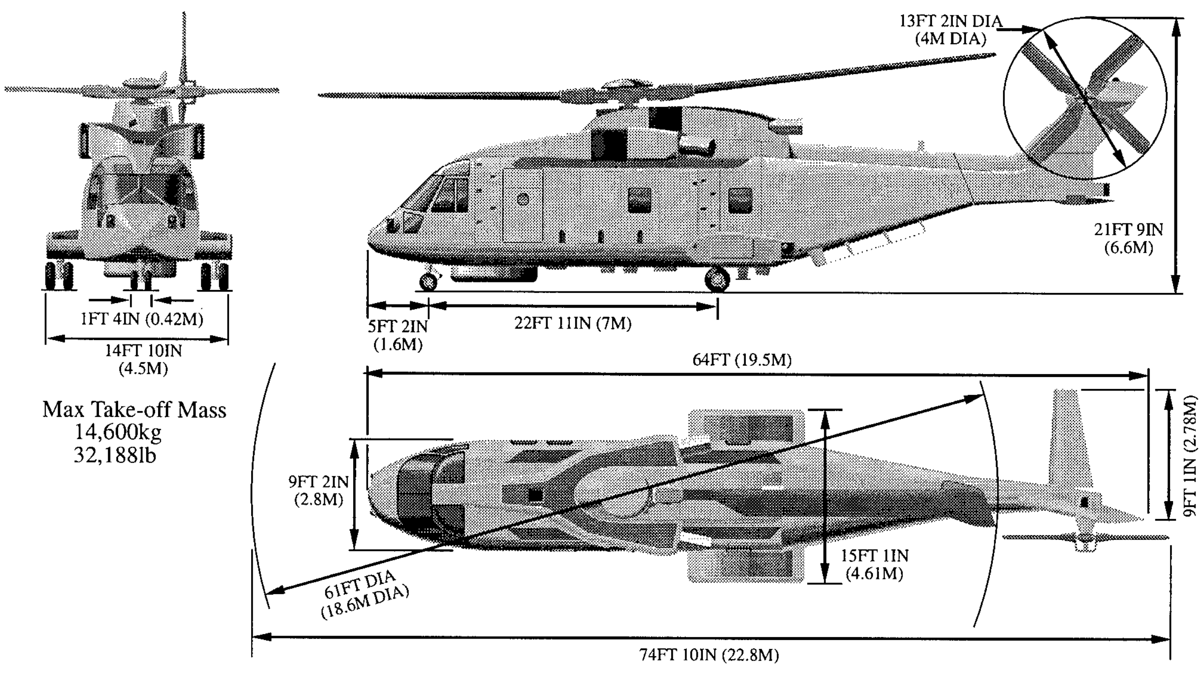


Figure 4 **EH101 LEADING CHARACTERISTICS**

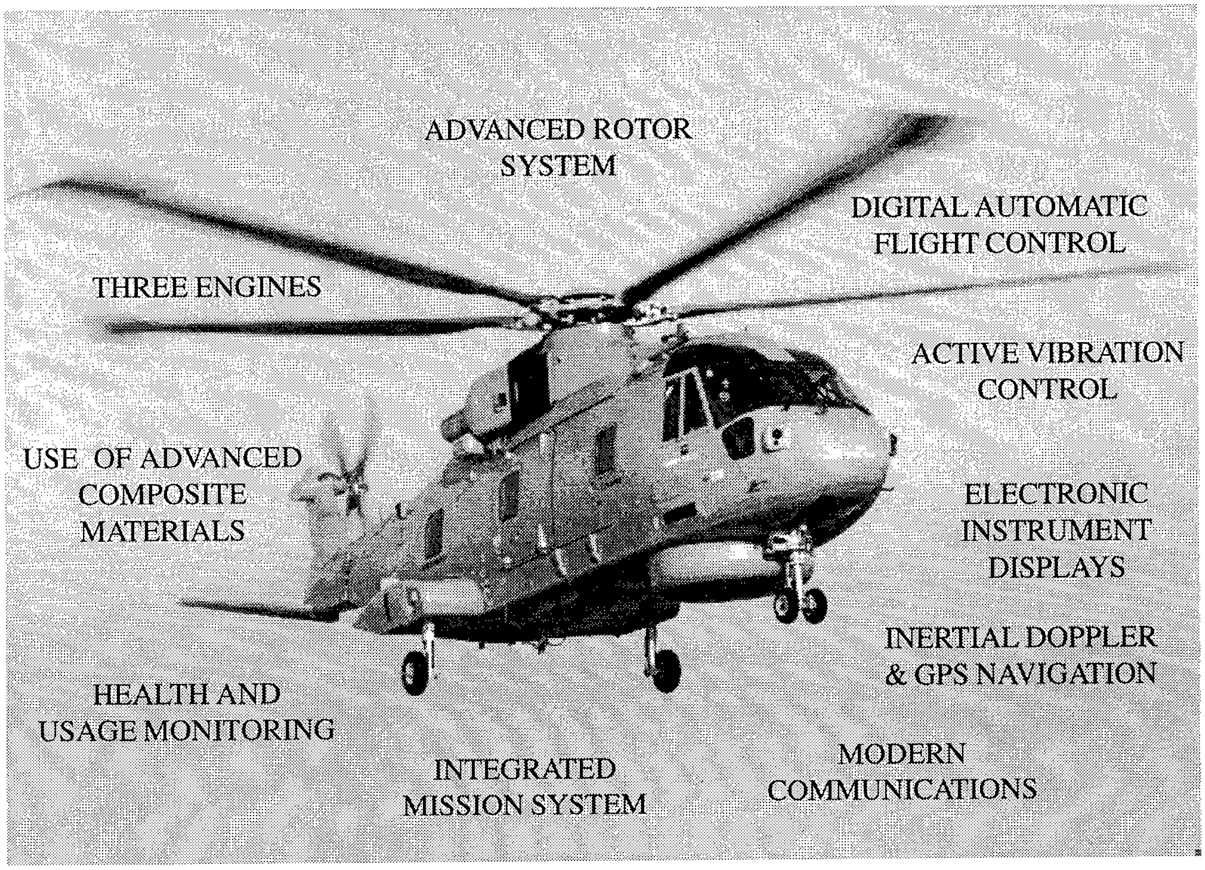


Figure 5 **MERLIN ADVANCED TECHNOLOGY**

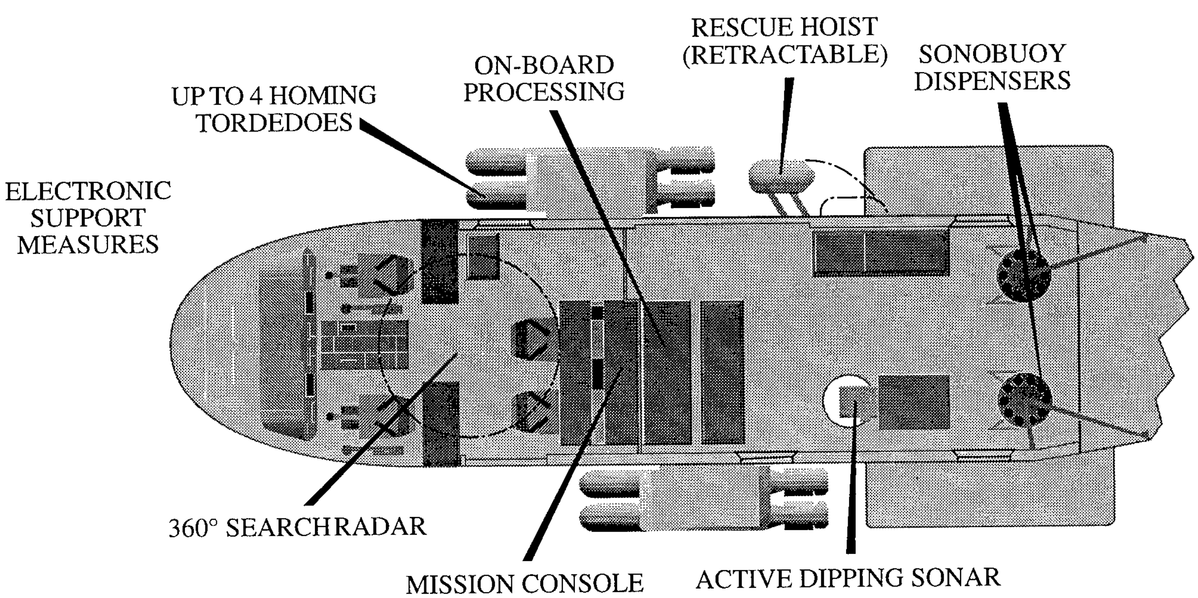


Figure 6 **COCKPIT AND CABIN LAYOUT (generic)**

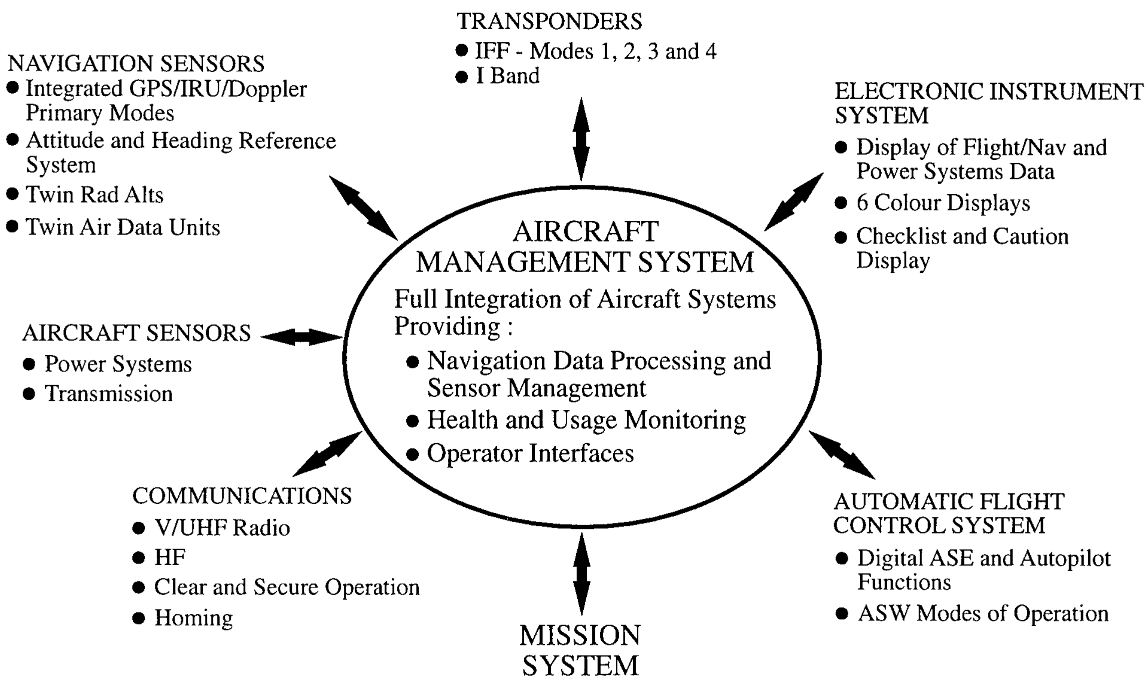


Figure 7 **CENTRAL ROLE OF AIRCRAFT MANAGEMENT SYSTEM**

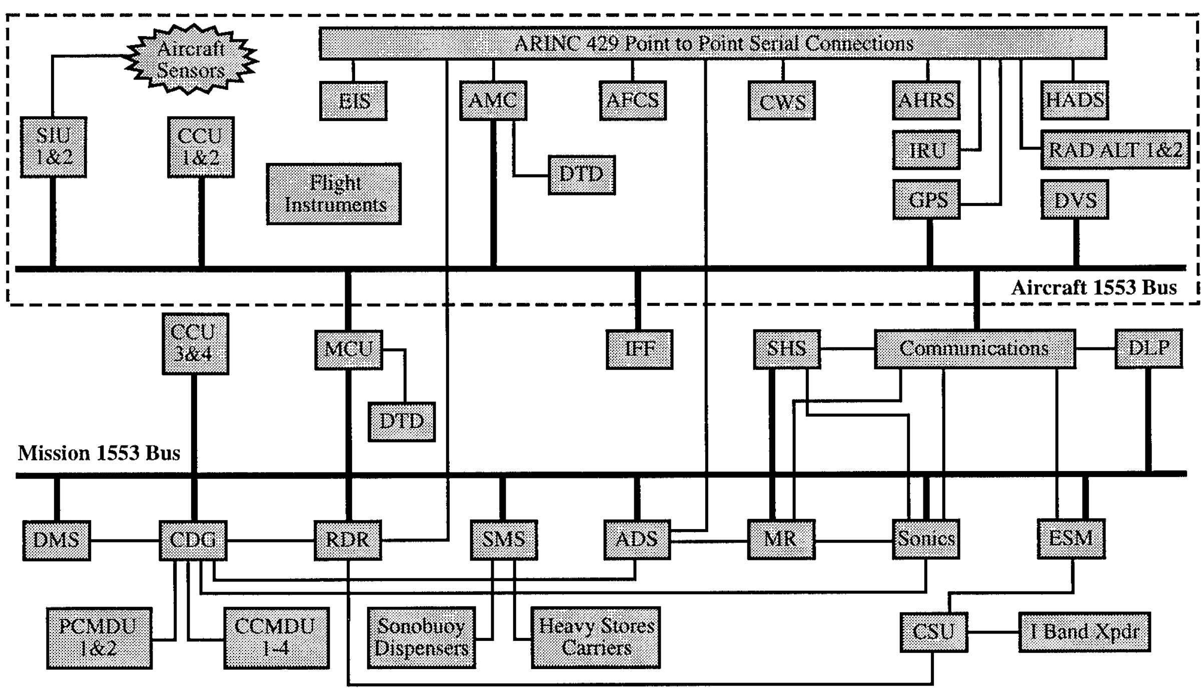


Figure 8 **MERLIN MK.1 ARCHITECTURE**

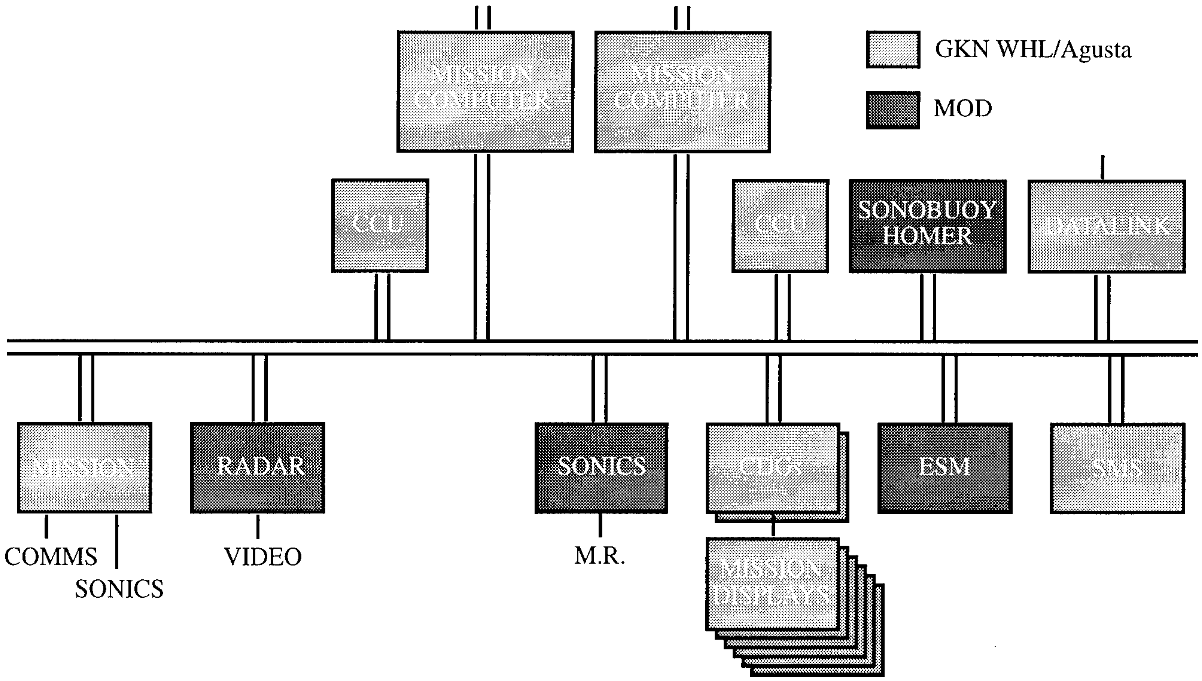


Figure 9 **MISSION SYSTEM**

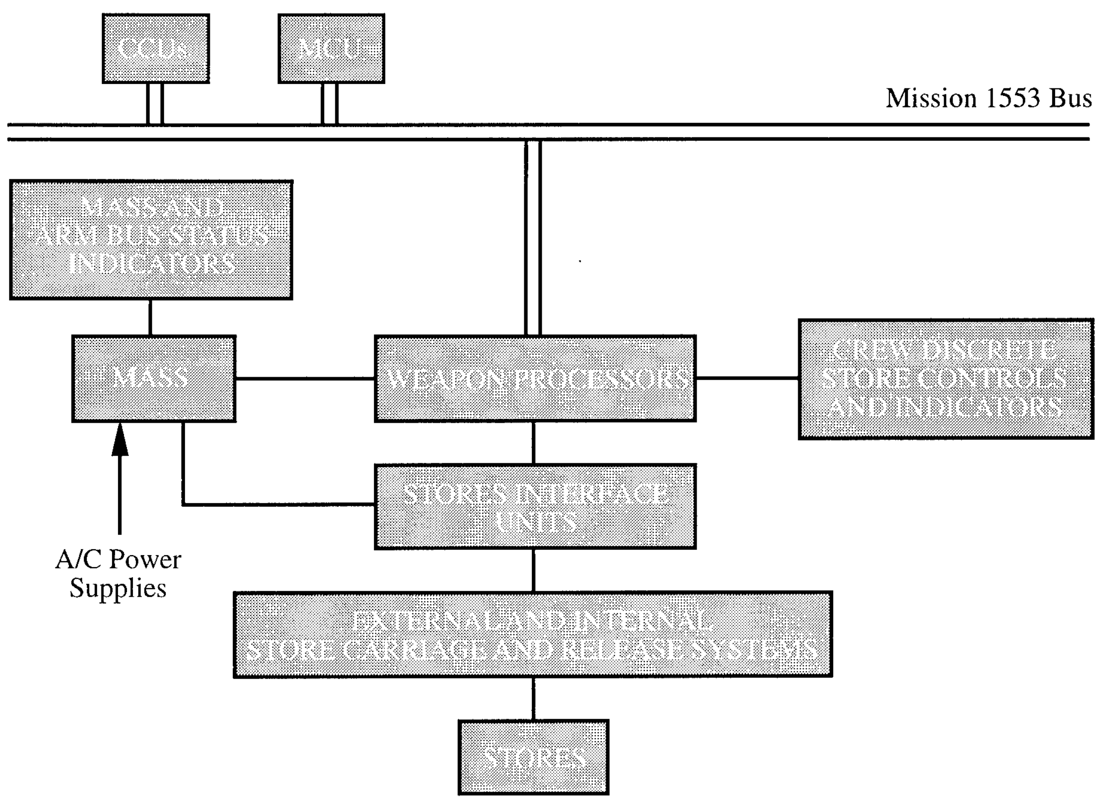


Figure 10 **STORES MANAGEMENT SYSTEM INTEGRATION**

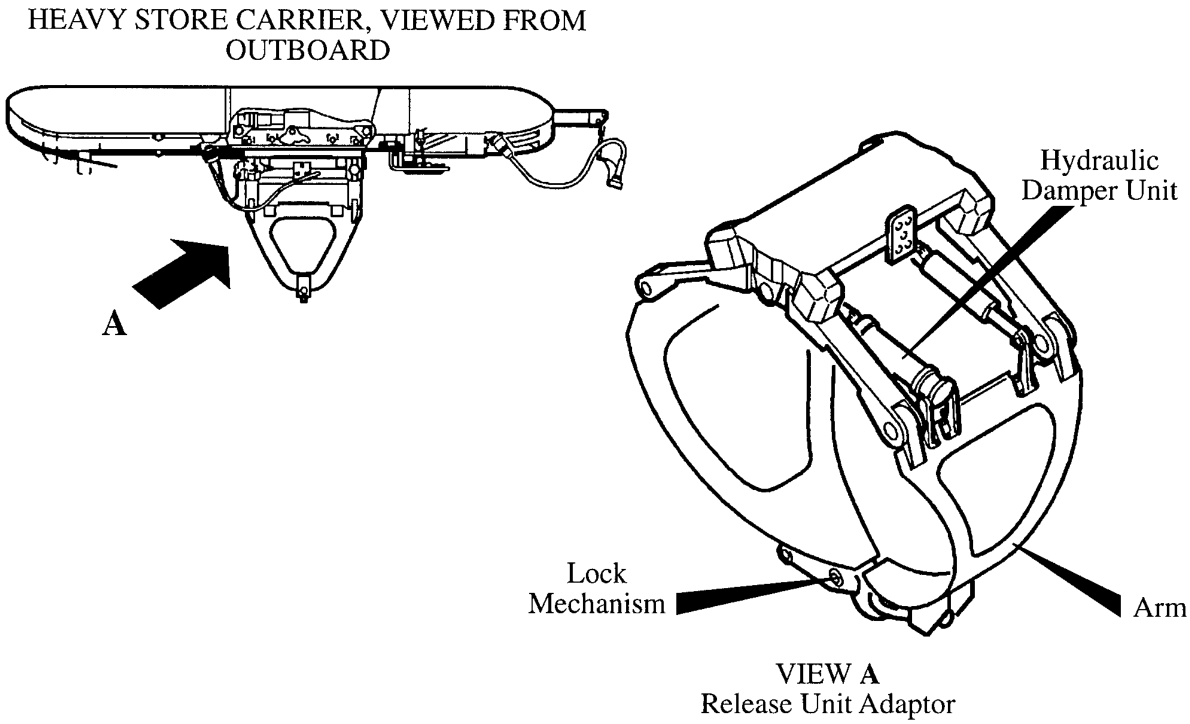


Figure 11 **MERLIN HEAVY STORE CARRIAGE**

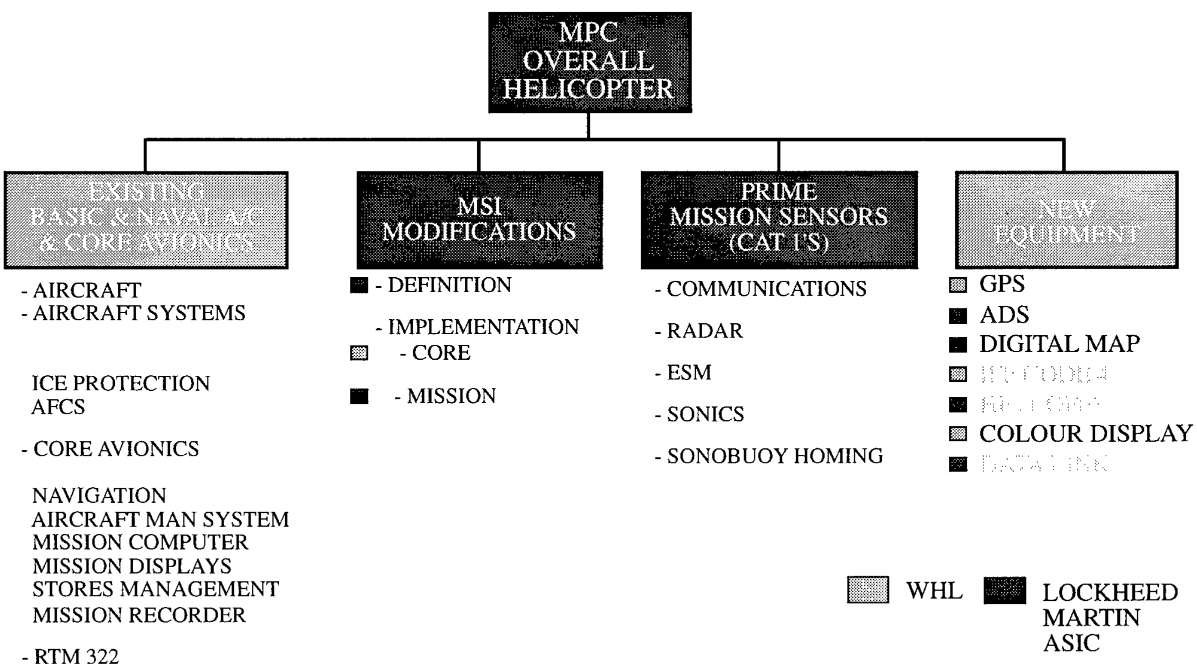


Figure 12 **EH101 MERLIN PRIME CONTRACT - LOCKHEED MARTIN ASIC / GKN WHL WORKSHARE MODEL**

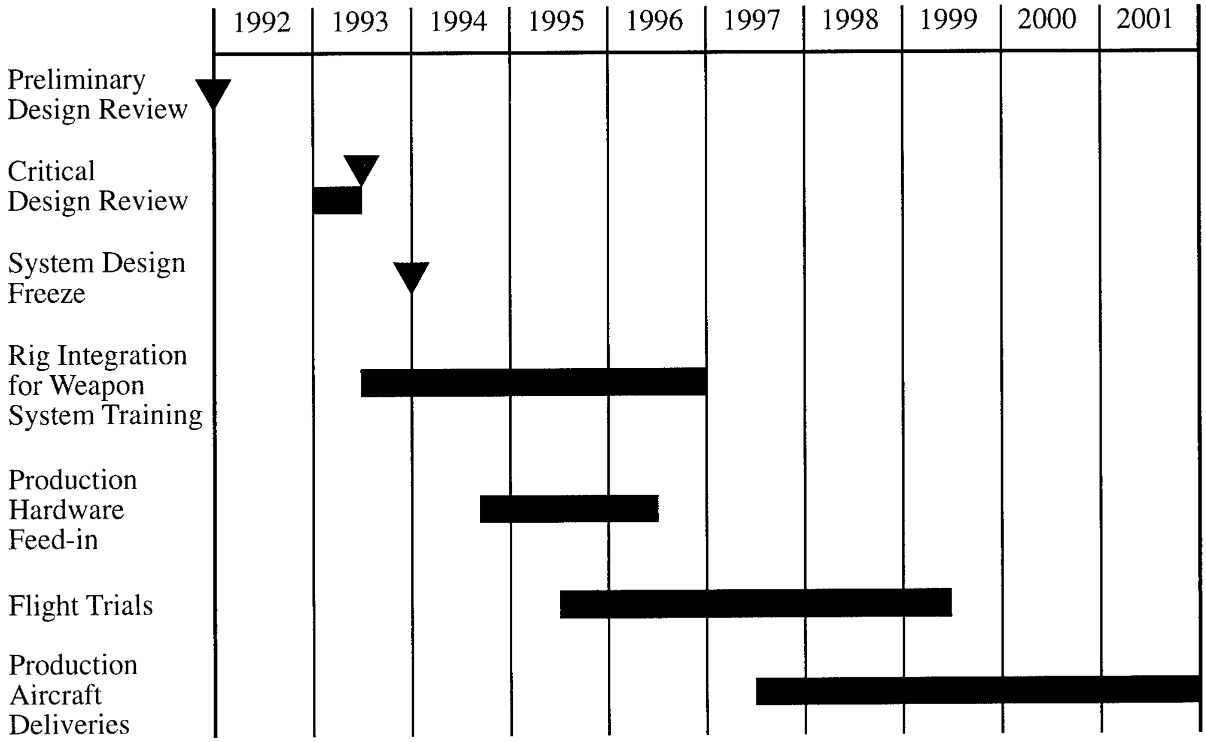


Figure 13 **MERLIN SYSTEMS INTEGRATION PROGRAMME**

Helicopter Weapon System Integration
Session 4: Case Histories
TIGER

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1. SUMMARY

The development of the TIGER helicopter/weapon system is a joint effort at equal parts of Germany and France to meet the requirements for combat support, air-to-air protection, escort, reconnaissance and anti-tank helicopter missions in post cold-war conflict scenarios. From a basic helicopter and avionics system the following versions are derived

- for France:

Combat Support TIGER (HAP)
.. with roof mounted sight, a chin mounted cannon, air-to air missiles and unguided rockets

Anti-Tank TIGER (HAC)
.. with mast mounted sight, air-to-air and anti-tank missiles

- for Germany:

Support TIGER (UHT)
.. with mast mounted sight, air-to-air and anti-tank missiles, unguided rockets and fixed gun pods .

After a short presentation of this versatile weapon system the lecture concentrates on a selection of mechanical integration example cases from the TIGER vehicle development and pre-qualification phase:

- Impact of main rotor downwash on launch error of unguided rockets
- Level flight pitch attitude optimization for missile launch
- Optimization of the main rotor system for aggressive manoeuvering requirements
- Main rotor blade/missile trajectory clearances
- Dynamic tuning for optimal vibrational behaviour
- AFCS gun compensation effectiveness
- Jettissoning of external stores

An overview on the general weapon system integration testing effort concludes this lecture.

2. ABBREVIATIONS

A/A	air-to-air
AFCS	automatic flight control system
AGL	above ground level
ALAT	Aviation Légère de l'Armée de Terre
ANAV	autonomous navigation
APU	auxiliary power unit
ATA	anti-tank armament
ATAM	air-to-air missile
AVT	Avionikversuchsträger
DLR	Deutsche Forschungsanstalt für Luft-und Raumfahrt
DMG	digital map generator
DNW	Deutsch-Niederländischer Windkanal
ECD	EUROCOPTER DEUTSCHLAND
ECF	EUROCOPTER FRANCE
FADEC	full authority digital engine controller
FAR	Federal Aviation Regulations
GPS	global positioning system
HAC	Hélicoptère anti-char
HAP	hélicoptère d'appui et protection
IAS	indicated airspeed
MEP	mission equipment package
MFD	multifunctional display
MGB	main gearbox
MMI	man-machine interface
MMS	mast mounted sight
NOE	nap-of-the-earth
OGE	out of ground effect
ONERA	Office National d'Études et Recherches Aéronautiques
PAH2	Panzerabwehrhubschrauber der 2. Generation
PT	prototype
TB	Thomson Brand
UHT	Unterstützungshubschrauber
Vh	maximum level flight speed

3. THE TIGER PROGRAMME

The development of the TIGER helicopter/weapon system is a joint effort at equal parts of Germany and France to meet the future needs of the French ALAT and the German HEERESFLIEGER (Army Air Corps). TIGER is optimized to fulfil multiple mission requirements for post cold-war conflict scenarios over a wide range from air-to air protection to ground support and anti-tank roles (Fig. 3 - 1). Main contractor in this programme is EUROCOPTER, a subsidiary of AEROSPATIALE and DAIMLER-BENZ AEROSPACE (DASA). In the programme the following milestones can be outlined (Fig. 3 - 2):

December 1987: Signature of the development contract by the two governments
April 1991: First flight of PT1, the first one of five prototypes, start of basic helicopter testing
December 1994: First Flight of PT4 in the French combat support version HAP, as a fully testable weapon system.
February 1996: First flight of PT5 in the German anti-tank version PAH2, as a fully testable weapon system.

Up to 31.12.96 all the prototypes have accumulated 1482 flight hours. The series preparation contract is expected for mid of

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1997. At the same time an amendment contract is awaited which covers the development efforts for the transition of the cold war German anti-tank version PAH2 into the multi-purpose support version UH-TIGER (UHT) as well a refined definition of the French combat support TIGER HAP.

4. THE TIGER WEAPON SYSTEM

The TIGER weapon system concept is founded on a basic helicopter platform and avionic system (Fig. 4. - 1). From this core three special versions are derived:

- for Germany:

Support TIGER (UHT)
.. with mast mounted sight, STINGER ATAM and anti-tank missiles either HOT (wire-guided) or TRIGAT (long range fire and forget) plus unguided rockets and 12.7 mm fixed gun pods.
External fuel tanks for extended range and ferry.
Missions: combat support, escort, anti-tank, reconnaissance, A/A self protection

- for France:

Combat Support TIGER (HAP)
.. with roof mounted sight, GIAT 30 mm chin mounted cannon, MISTRAL air-to air missiles (ATAM) and TB 68 mm rockets.
External fuel tanks for ferry.
Missions: Air-to-air protection, ground support, escort, armed reconnaissance

Anti-Tank TIGER (HAC)
.. with mast mounted sight, MISTRAL ATAM and anti-tank missiles either HOT (wire-guided) or TRIGAT (long range, fire and forget).
External fuel tanks for ferry.
Missions: Anti-tank, A/A self protection, reconnaissance

The features of the specific mission equipment packages (MEP) for the UHT and the HAP can be seen in fig. 4 -2 and 4 -3. Due to the 30 mm cannon and the TB 68mm rocket pods the French combat support helicopter HAP had a specially tailored MEP version, the HAP-MEP.
The former common mission system for the French and German anti-tank versions HAC resp. PAH2 , called EUROMEP, covering the gunner and pilot visionics with the anti-tank armament plus its controls, is now enlarged for the German UHT to additionally operate podded guns and rocket pods.
Feasibility studies to integrate under the UHT chin a recoilless MAUSER 30 mm turreted gun are on the way at this moment.
Common for all TIGER types is the capability of flight and combat in night and adverse weather conditions. This is provided by a sensor system with IT- and TV-cameras and image intensifier tubes. Presentation of different sensor images and their use by the crew is allocated according to their primary and secondary task for either piloting or weapon operations.
The sight systems in combination with the navigation system (ANAV with GPS), the digital map generator (DMG) and the tactical situation managment of the mission system computers as well as the multifunctional displays (MFDs) in the cockpits allow an autonomous operation of the TIGER.
A 4-axis digital automatic flight control system (AFCS), consisting of redundant computers, supports the pilot not only in basic aircraft stabilisation but remarkably reduces workload in the cockpit through its auto-pilot modes like attitude hold, IAS hold/ capture and hold of altitude and heading, etc. More weapon application specific are the AFCS modes like capture and hold of line-of-sight or gun firing compensation in attitude.
These mission system features based on a modern helicopter platform concept, provide a high effectiveness in military operations, supportability and logistics for the customer (Fig. 4 - 4). Further information on the TIGER weapon system and avionics is given in /4/, /5/, /6/.

5. THE TIGER WEAPON PLATFORM - FEATURES AND PERFORMANCE

5.1 Vehicle Features

TIGER's take-off mass is located in the range between 5000 to 6000 kg. The design take-off mass is 5400 kg. The weaponry and ferry tanks in different mission configurations give take-off mass variations about this value. Main dimensions can be taken from fig. 5.1 - 1. Important vehicle features are summarized in fig. 5.1 - 2. Some additional informations on those vehicle features, which might be important for the understanding of weapon system integration problems may be given here.

..Airframe
Peculiar in the appearance of this helicopter is the narrow front silhouette fuselage. The airframe is entirely made of composites, with modular equipment compartments using the ARINC 600 concept. By contract, landing gear and airframe structure have to fulfil 90% of the crashworthiness requirements of MIL -STD-1290.

.. Main Rotor
TIGER's high agility and excellent controllability is provided by a hingeless composite main rotor with 10 % equivalent flapping hinge-offset. The functions for centrifugal retentention, blade shear force transfer and blade pitch motion are taken over by a conical and a radial elastomeric bearing in the hub arms. The 4-bladed rotor has a diameter of 13 m. A solidity of 9.7% indicates good future growth potential from the design take-off mass of 5400 kg, with then still attractive load factors.

.. Tail Rotor
Anti-torque and yaw manoeuverability is rendered by the powerful 3-bladed, 2.7 m diameter tail rotor of the type SPHERIFLEX. By this, TIGER has outstanding lateral and yawing flight performance: e.g. heading change by 40°
after 1 sec, standing side winds of 50 kts, high lateral mask and unmask agility.

..Engines and Main Gear Box
TIGER is powered by two MTR390 engines, each producing 958 kW as a maximum for take-off. Robustness of operation is provided by the twin centrifugal compressor design. The engine is controlled by a full authority digital engine control (FADEC) incorporating also useful monitoring functions. The MTR390 engine is developed in a parallel programme especially for TIGER by the MTR consortium consisting of TURBOMECA, DASA-MTU and ROLLS ROYCE in contract to the German and French governments.
The 3 stage main gear box (MGB) has been specified to 1468 kW max. cont. power at Nr= 328 rpm . The MGB has a dry run capability of 30 min., which could already successfully be

proven in a qualification test. A special clutching/ declutching device and logics allows an APU operation on one engine.

.. Anti-Resonance System

TIGER possesses a highly efficient anti-resonance system, SARIB, reducing remarkably the 4/rev-vibrations induced by the 3 and 5/rev harmonic hub loads of the high hinge-offset main rotor. SARIB allows a reproducable vibration tuning for the later series aircraft.

5.2 Performance and Flight Envelope

Main performance features can be taken from the chart depicted in fig. 5.2 -1. TIGER's nap-of-the-earth (NOE) flying capability is assessed by the power reserve available in hover OGE without wind. In qualification performance flight tests the specified NOE power reserve of 17% at 1000m, 25°C for design take-off mass of 5400 kg could be demonstrated. This is in line with the more commonly known requirement that combat helicopters should be able to vertically climb with 1000 ft/min at take-off power.

In a qualification flight and ground loads substantiation test program the airframe and dynamic system structures of TIGER have proven their fitness for aggressive combat manoeuvres as they are required in the ADS 33C handling qualities requirements for military aircraft. Moreover TIGER has full aerobatic capabilities, thus revealing its suitability for the air-to-air combat /3/.

The demonstrated load factor - speed envelope is shown in fig. 5.2 - 2. In all extreme main rotor blade loading situations the aircraft is showing an excellent controllability without excessive vibrations. The high blade loadings in coordinated turns at low speeds could be achieved by application of the 2nd generation helicopter blade airfoils DMH3, DMH4 on the main rotor. These airfoils are a common development of the German DLR and EUROCOPTER. High speed capability is due to a low relative airfoil thickness of 9% and the parabola shape of the main rotor blade tip (layout by the French ONERA).

All this technology is applied to serve the needs of the demanding operative elements in the TIGER missions, as an example of which, here the combat support/day mission profile is shown in fig. 5.2 - 3.

6. WEAPON SYSTEM INTEGRATION

6.1 A Selection of Integration Example Cases from the TIGER Development and Pre-Qualification Phase

6.1.1 Impact of Main Rotor Downwash on Unguided Missile Launch Error

The induced flow field (downwash) beneath the main rotor is of great interest for the study of trajectory detoriations of unguided missiles like rockets directly after launch.

The principle influence of a downwash of 15 m/s produced by a helicopter hovering at 150 m height AGL on the trajectory of a rocket is shown in fig. 6.1.1 -1. In this computer simulation study the rocket has a range error of nearly the range obtained under undisturbed conditions. This is due to the downwash impact onto the stabilisation fins of the rocket producing a significant nose-up moment. The trajectory is similar to that one after a launch with super-elevation angle without downwash.

Aside this military application aspect, the induced velocity field prediction and measurement are of general interest in the context of interferences with the fuselage and/ or stabilizing surfaces.

In modern rotorcraft analysis computer codes induced velocity calculation options are offered using complex prescribed and free geometry wake models. Meaningful application of these wake models already requires the adaption of important empirical wake parameters like vortex core diameter or initial blade radial vortex location to windtunnel experiments. A disadvantage of these calculation methods is the fact that they are using iterative solving techniques of the governing non-linear equations.

For downwash studies applied to TIGER an empirical approach has been chosen. Induced velocity data obtained from model rotor measurements performed by the DLR in the German-Dutch Windtunnel DNW have been normalized and scaled to TIGER main rotor dimensions and speed conditions.

For this an example calculation of the 3 induced velocity components at a location 2 m beneath the rotor and right lateral offset of 2 m for hover and different level flight aircraft speeds is presented in fig. 6.1.1-2. The development of the vertical and longitudinal components of the induced velocity with respect to the longitudinal coordinate reveal a certain sensitivity with helicopter forward speed respectively with wind from the front.

6.1.2 Level Flight Pitch Attitude Optimization for Missile Launch

As already reported in /2/ the optimization of the tailplane location, size and aerodynamic shape was an important subject of early TIGER flight testing.

Main objectives were the following:

(I) Support static and dynamic stability

(II) Low nose-up aircraft pitch attitude effect in the forward speed range at 30-40 kts, when the downwash impinges the tailplane

(III) As low as possible nose-down pitch attitude in level flight at Vh

Objective (I) will not be discussed here further because it is referring to a standard in-flight development step.

Objective (II) is important for the weapon delivery at stationary transition forward speeds or (and what is operationally more interesting) with wind coming from the front direction. Significant, unintended elevation of the weapon stores via the helicopter pitch attitude should be avoided.

Objective (III) is addressing air-to-air missile and rockets firing. Some air-to-air missile drop down a considerable vertical distance in the phase between launch motor burn-out and ignition of the main propulsion. There is the potential danger of loosing the weapon when fired in ground vicinity. Concerning rocket firing, less nose-down attitudes allow to pull the aircraft much more quickly into super-elevation angles.

Five tailplane configurations have been flight tested (see the table in fig. 6.1.2 -1). The ability of TIGER to fly approx. 170 kts without any tailplane due to its excellent controllability by the high hinge-offset main rotor was of great help to establish a clean reference for the different tailplane versions.

The final production type tailplane is the configuration 5 which uses a tab and a Gurney flap at the trailing edge. An airfoil nose spoiler on the upper side (with reference to aircraft axes) has been finally added to minimize the collective control offset between power-on and power-off operation.

The final tailplane angular setting and the application of the additional trailing edge aerodynamic aids have been accomplished in a compromise between tailplane stall at high speeds in gusty conditions, main rotor mast pitching moment for endurance and the aircraft pitch attitude at Vh (see fig. 6.1.2-2).

The final result for the longitudinal trim of TIGER is shown in fig. 6.1.2-3.

4.1.3 Adaptation of the Main Rotor System Structure to Aggressive Manoeuvering Requirements

Early flight testing with PT1 revealed a certain weakness of the 1st main rotor version to stand dynamic loads in high load factor manoeuvres. Fatigue life would have been substantially reduced . There has been a significant excess of stress limitations for blade lead-lag, blade neck torsion and longitudinal hydraulic control booster force (reversibility limit for operation on one hydraulic system only) above load factors of 2 g (ref. 5400 kg).

The first version of the main rotor blade had a built-in droop angle of 2.5° in the transition region between the centrifugal retention lug and the blade neck. A central hub coning angle was missing. This geometry has been chosen during the definition phase to provide more aerodynamic coupling damping via the blade pitch and lead-lag motion sequence.

Concerning the loads, it was clearly recognized that this geometry gives an unfavourable offset between the blade and its pitch control axis. Thus already by the "normal" cyclic control input rather high blade lead-lag and pitching torsional reactional moments were introduced. This situation got of course worse with the additional static elastic blade flap bending at high load factors.

Early ground and air resonance checks on PT1 demonstrated comfortable stability margins. The risk of a too low lead-lag blade damping was also minimized by the existence of the fluid lead-lag dampers. Consequently it was decided to eliminate the blade droop angle and to introduce into the hub center a coning angle of 2.5° for dynamic loads relief (fig. 6.1.3-1).

This change together with some flapping effective reinforcements in the blade neck and the composite hub plates was introduced in the so-called "upgraded" main rotor version.

An intensive flight and ground loads qualification testing according to FAR29.571 /8/ with extensions to aggressive mission task elements of. the ADS 33C /7/ (e.g. rapid accelleration, decelaration, pull-up/push-over, rapid slalom, transient turn and roll reversals, etc.) fully confirmed the load reduction effect of this hub geometry change. Thus TIGER now offers more than the flight/envelope specified by the French/German customer.

For the "Upgraded Main Rotor" the Fig. 6.1.3-2 gives a view over the alternating (1/rev) part of the flapping moments, here expressed in main rotor shaft and the blade lead-lag bending moments.

As one can see, ground operations like quick taxiing accelerations and slope landings produce the highest mast bending moments with rather low lead-lag moments (more or less only Coriolis loads). This was expected for the high hinge-offset main rotor design.

High lead-lag loads with fair flapping loading are produced in steady turns at maximum blade loading and aggressive instationary manoeuvres like symmetric pullout or rolling pul-out. The dynamic lead-lag loading originates from a high aircraft trajectory speed, high longitudinal cyclic control input and high static elastic blade flapping due to the load factor. Additional sudden lateral cyclic control inputs as for the rolling pull-out intensifies the lead-lag loading.

6.1.4 Main Rotor Blade Clearances to Missile Trajectories

Another task of mechanical weapon system integration is the check of the main rotor blade clearance to weapon trajectories. Push-over flight manoeuvres and aggressive forward taxiing are here the most critical aircraft operating conditions.

The elevation hard stops of the chin mounted cannon as well as of the stores under the wing have to be determined according to the downward flapping capability of the main rotor in the front quadrants of the rotor disk (Fig. 6.1.4-1). For the cannon, the air-to-air missiles and for the unguided rockets the whole flight domain has to be considered with respect to push-over manoeuvres. Anti-tank missiles are more likely to be used in near-hover or moderate level flight conditions.

The table of fig. 6.1.4-1 gives information of minimum flapping angles, resp. blade tip deflections for different operating cases, either calculated or obtained by flight test measurements.

For TIGER the minimum load factor is specified to -0.5g. Thus, minimum flapping of -7.8°, calculatory occuring at -1g (case 1) can be already regarded as an exceedance of the structural flight envelope. Moreover is this valid for the limit load flapping angle of -10.3° equivalent to 1.06 m blade tip deflection (case 0) beneath the plane rectangular to the rotor mast. This situation can only be reached in an uncoordinated, transient emergency flight situation which anyhow is critical for the structural integrity of the aircraft apart from any tactical manoeuvre. As a first simple rule, this angle is recommended for the specification of the elevation hard stops.

There is a comfortable margin to extreme cases occuring in prototype flight test like case 3 a push-over with only half the value of limit load flapping.

6.1.5 Tuning for Optimal Vibration and Dynamic Loads Behaviour

During the first flight tests with PT1 high vertical vibration levels in 4/rev at the crew stations were measured. This vibrational level was lying outside the tuning capabilities of the anti-resonance system SARIB. It was necessary to adjust the 2nd flapping mode of the main rotor blade such that its eigenfrequency would be clearly positioned below the 3/rev excitational rotorharmonic. Some masses had to be added into the blade midpoint of the rotor radius.

In order to reduce the 4/rev drive train steady state torque oscillations a further optimization step was performed by internally stiffening the trailing edge of the blade airfoil part with a carbon strip. This shifted the 2nd blade lead-lag eigenfrequency more above the 5th rotor harmonic. Thus, the 4/rev drive train oscillatory torque could be reduced by 50% in the whole level flight range.

The actual situation for the main rotor blade eigenfrequencies for flapping, lead-lag and torsion is shown in the frequency diagram in fig. 6.1.5-1.

4/rev vibrations in the airframe originate mainly from the 3/rev rolling and pitching moments and inplane shear forces in the rotating axis system of the main rotor hub. 5/rev contributions are less significant because the 2nd flap bending eigenfrequency of the blade is located nearer to the 3rd rotor harmonic.

Further optimization efforts for vibration reduction at the crew stations and at the mast mounted sight (MMS) focussed on the tuning of the anti-resonance system SARIB and MMS support structure.

The SARIB system (Fig. 6.1.5-2) is adjusted via the resonator flapping masses which are responding to the 4/rev rolling and pitching motions of the MGB/ main rotor assembly mounted on a soft in bending, stiff in torque diaphragm /1/.

The final result after these tuning efforts is depicted in fig. 6.1.5-3 for the 3/rev hub loads and the vertical 4/rev vibrations at the pilot station versus level flight speeds.

Linear vibration levels of the MMS in 4 and 8/rev relative to the specified interface values of the TIGER programme are shown in fig. 6.1.5-4. The 4 and 8/rev linear vibration levels at all MMS locations are comfortably within the specified values for the full MMS performance.

6.1.6 AFCS Gun Compensation

The 30 mm chin mounted, turreted gun of the TIGER HAP produces considerable recoil forces. For the gun can be operated in azimut and in a wide elevation range, moments about all axes are exerted on the helicopter which are disturbing its initial attitude. This can be seen in fig. 6.1.6-1 in the downward diagram series with time histories entitled AFCS OFF. The activity of the cannon can be seen from the trigger signal (bottom diagram) and on the vertical acceleration of the strapdown navigation measurement. The cannon is in neutral azimut and elevation position. During and after this short burst of approx. 1 sec only , the helicopter changes pitch attitude by approx. 5 deg. nose-down.

The right hand side time histories (AFCS ON) in fig 6.1.6-1 demonstrate the effectivity of the gun compensation branch in the AFCS. During and after gun fire the helicopter pitch attitude remains undisturbed.

6.1.7 Jettisoning of Stores

In emergency situations the option is required to jettison the weapon stores from under the wing. The most interesting flight state is here the autorotation. A special flight envelope in forward and descent speed, indicating the avoid areas, where the most critical launcher would hit the helicopter has to be provided for the flight manual.

In the TIGER programme to date, the jettisoning of an empty MISTRAL launcher from PT4 (HAP) at 100 kts forward speed and a descent rate of 2800 ft/min has been succesfully demonstrated during a firing campaign. Jettisoning tests of empty STINGER launchers from PT5 (UHT) are expected in the nearest future. The empty STINGER launcher is expected to be the most critical one for jettisoning because it has the lowest mass in the TIGER weapon launcher suite.

To study in detail the jettisoning behaviour of different stores a two-dimensional, mathematical ballistic model was built. This model should give information about the CG trajectory in longitudinal and vertical translation as well as about the pitch attitudes of the dropped launcher. Basis for the calibration of this model was the aerodynamic polar data from a full scale STINGER windtunnel test and further the photographically measured trajectories of the TIGER launcher models (STINGER, HOT, TRIGAT, MISTRAL) in the scale of 1:8.4 of windtunnel tests performed at EUROCOPTER France (ECF).

Also the aerodynamic characteristics of the isolated TIGER launchers had been measured in the ECF windtunnel but only in a small range of angles-of-attack and sideslip. The necessary extension of these data for large incidence angles has been tailored using the STINGER full scale aerodynamic polars which consider angles all around 360 degs.

There were no difficulties to simulate the launcher trajectories of the small scale windtunnel tests of ECF. A fair coincidence of results was obtained as concerns the CG dropping paths of the different launchers (see fig. 6.1.7-1). However it was difficult to verify the tumbling behaviour of the launchers in the early motion phase.

A detailed analysis of the pitch-up behaviour with the theoretical model just after the release from the stubwing revealed that all launchers (also MISTRAL) would directly hit the stubwing nose at a certain forward speed without any descent rate of the helicopter. This was contradictory to experience gained in former weapon integration projects on BO105 and furthermore not inline with the earlier MISTRAL jettisoning demonstration. A video of this demonstration shows clearly that the MISTRAL launcher does not start the pitch-up motion immediately after separation from the wing but only when it is approximately 2 to 3 metres below the helicopter. From this fact it was deduced that for the early motion phase the angles-of-attack between model and reality are considerably different, most presumably due to the presence of the stubwing.

A good adaptation of the simulation model to the MISTRAL measurement was obtained by reducing the built-in launcher incidence angle by 50%. This was also retained for the motion calculations of the other weapon launchers.

Fig. 6.1.7-2 shows the jettisoning flight envelope obtained after this whole process. This chart is now the starting base for the future jettisoning tests with STINGER.

6.2 System Integration

Previous chapters have shown some examples of weapon system integration tasks related to aeromechanics as they occured during development and pre-qualification in the TIGER project. However this lecture should not conclude without giving an overview on the total system integration effort in the TIGER programme.

All sensitive subsystems like the MTR390 engine , the anti-tank armament with TRIGAT launcher and mast mounted sight, the pilot sight unit and additional German avionic options , i.e. the digital map generator (DKG) in combination with HF radio data communications are tested in flight on dedicated helicopters AS565, AS332 and BK117-AVT (Avionik-Versuchsträger) before installation on TIGER (see fig. 6.2 -1). These afore mentioned efforts are of course assigned to the parallel development programmes (e.g. MTR390, ATA /TRIGAT) in support to TIGER.

A suite of ground testing facilities is at the disposal to integrate the different subsystems of basic avionics and mission equipment up to functional chain testing of weapon launchers and sight systems (see fig. 6.2 - 2 and -3). Important to mention is that the MMI cockpit interfaces and functions for the avionics and weapon systems are developed together with the military user in special working groups.

7. CONCLUSION

A selection of weapon system integration example cases, as experienced during the TIGER vehicle development and weapons pre-qualification phase, has been presented. In these examples mainly problems of the aeromechanics area were reported including also the global efforts to optimize the helicopter structures for the specified mission tasks.

TIGER is now finishing the qualification of the vehicle. At this moment the industrial development tests to integrate the different weapon and sight systems are in progress.

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Literature

1. T. Krysinski, G. Seitz, "Overview of TIGER Dynamics Validation Program", 48th Annual Forum of the AHS, Washington, June 1992

2. A. Cassier, J.M. Pouradier, R. Wennekers, "Aerodynamic Development of the TIGER Helicopter", 50th Annual Forum of the AHS, Washington, May 1994

3. P. Rougier, W. Sinn, R. Wennekers, "The TIGER... New Potentials for a New Helicopter", 21st European Rotorcraft Forum, St. Petersburg, Russia, August 1995

4. EUROCOPTER INT. Sales Div. , "Focus on.... TIGER", Brochure, EUROCOPTER S.A. 1996

5. K.H. Stenner, "TIGER for the HEERESFLIEGER", The Fighter Helicopter Conference IV, London, January 1996

6. K. Rüskamp, "TIGER Avionics", Military Avionics Conference, London, May 1996

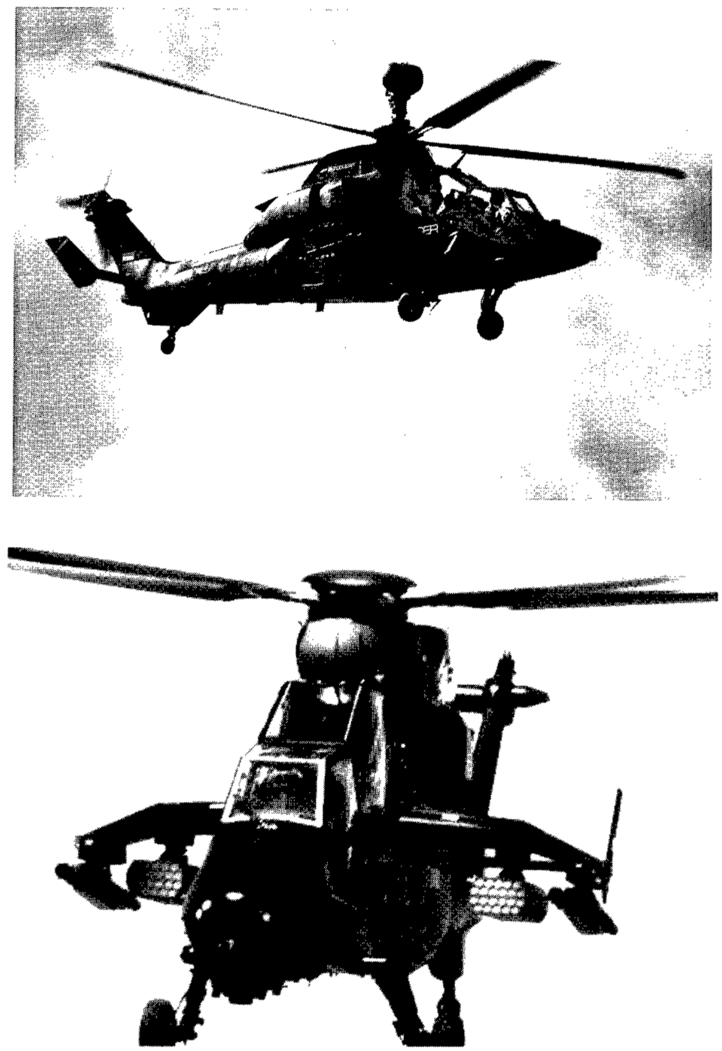


Fig. 3.-1: TIGER: UHT and HAP version

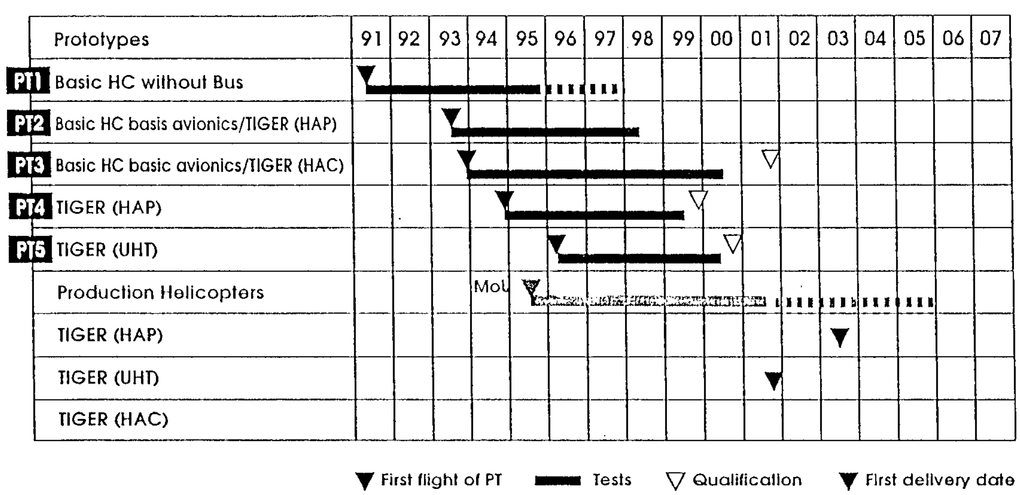


Fig. 3.-2: Prototype schedule

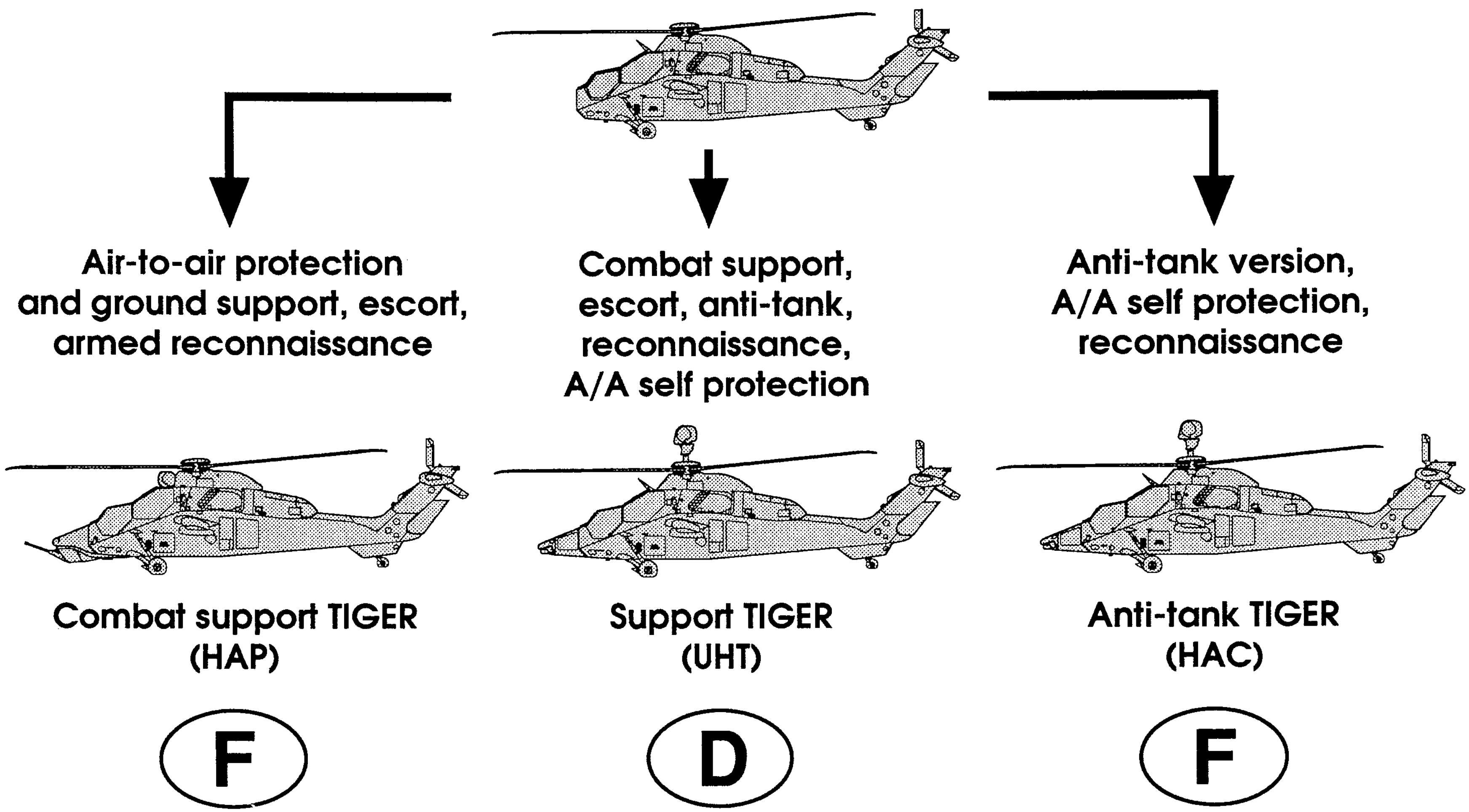
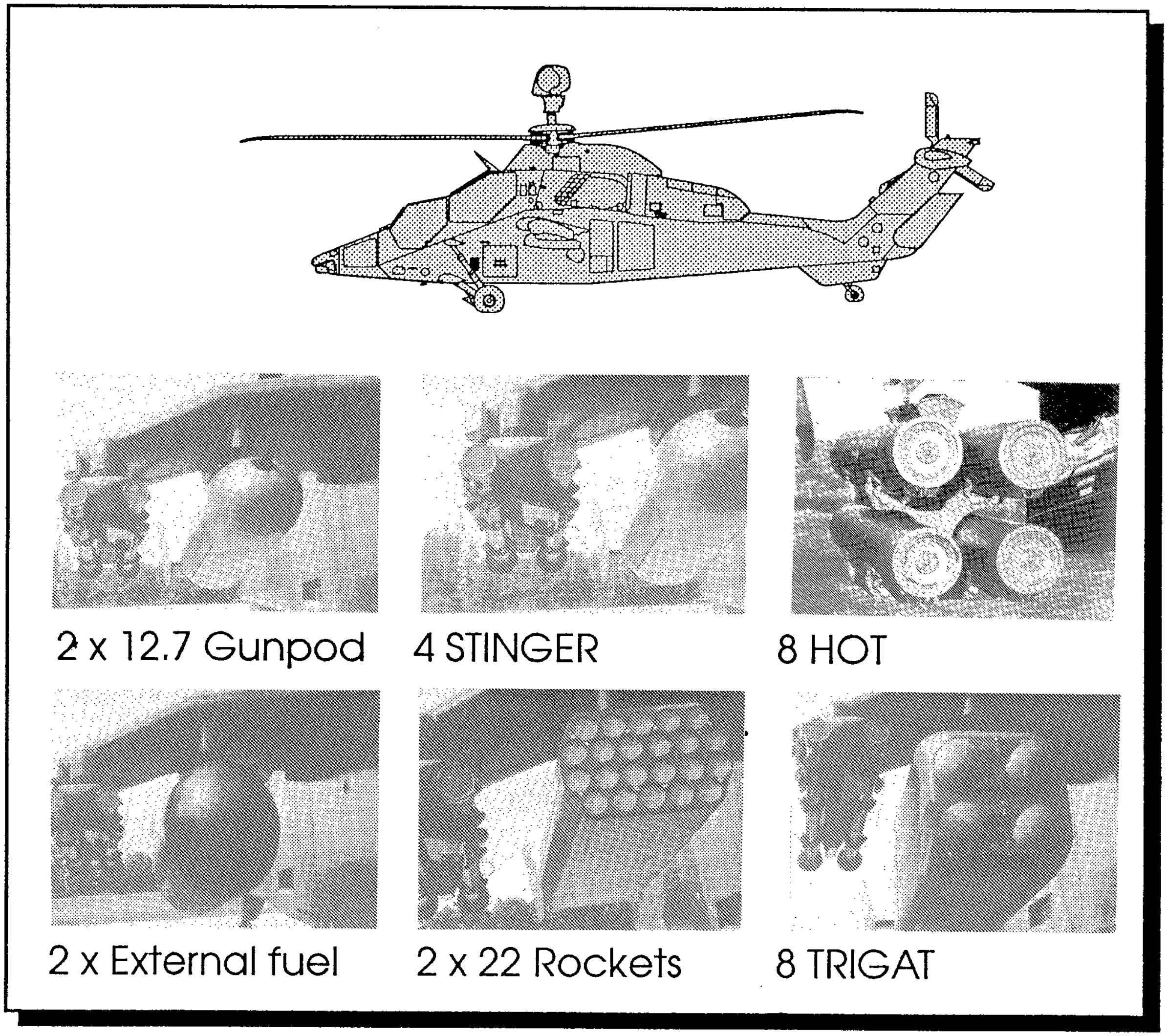


Fig. 4.-1: Weapon system concept



Pilot vision systems

- Thermal imager
- Helmet mounted sight/display (2)

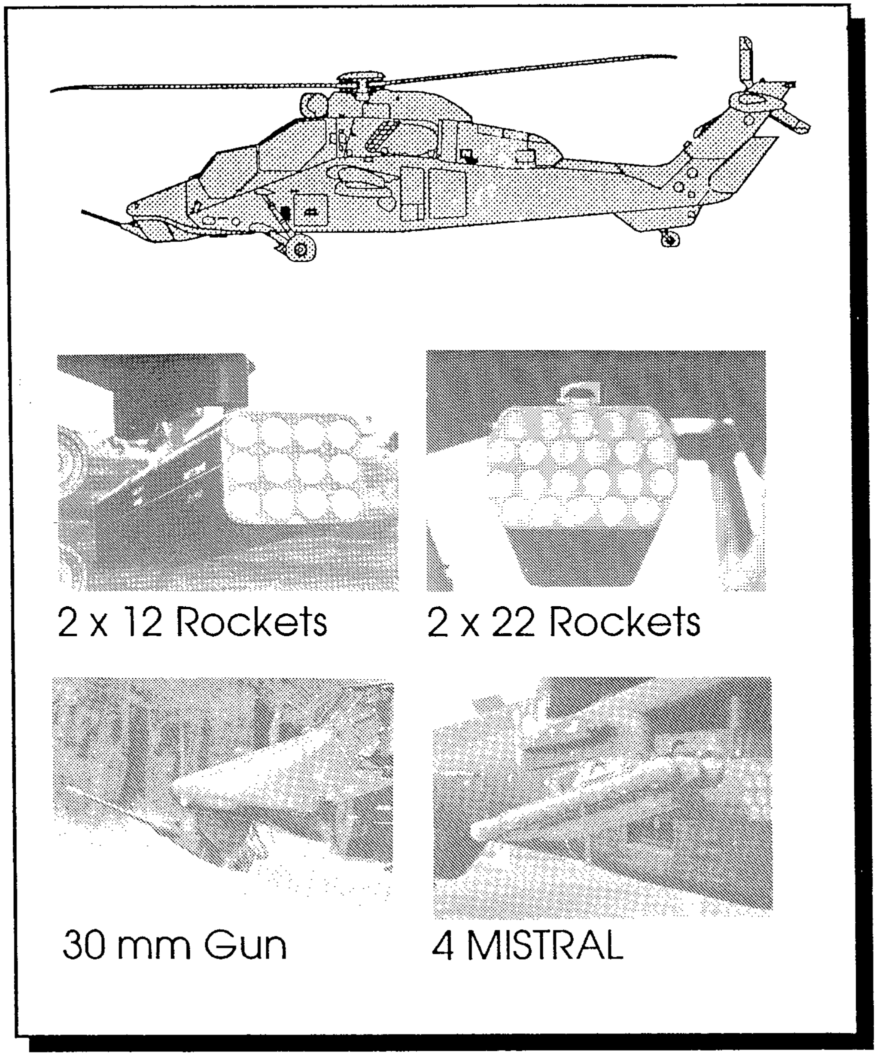
Gunner visionics

- TV camera
- Thermal imager
- Laser range finder
- Missile localizer

Armament

- 2 x 4 anti-tank missiles HOT or TRIGAT
- 2 x 22 unguided rockets
- 2 X 12.7 mm gun pod
- 2 x 2 A/A missiles STINGER

Fig. 4.-2: TIGER UHT: Mission equipment package



Pilot vision systems

- Head-up display
- Helmet mounted sight
- Night-vision goggles

Gunner visionics

- Direct view optics
- TV camera
- Thermal imager
- Laser range finder

} Roof sight

- Helmet mounted sight
- Night vision goggles

Armament

- 2 x 2 MISTRAL
- 30 mm turret-mounted gun capacity 450 rounds
- 2 x 22 unguided rockets
- 2 x 12 unguided rockets

Fig. 4.-3: TIGER HAP: Mission equipment package

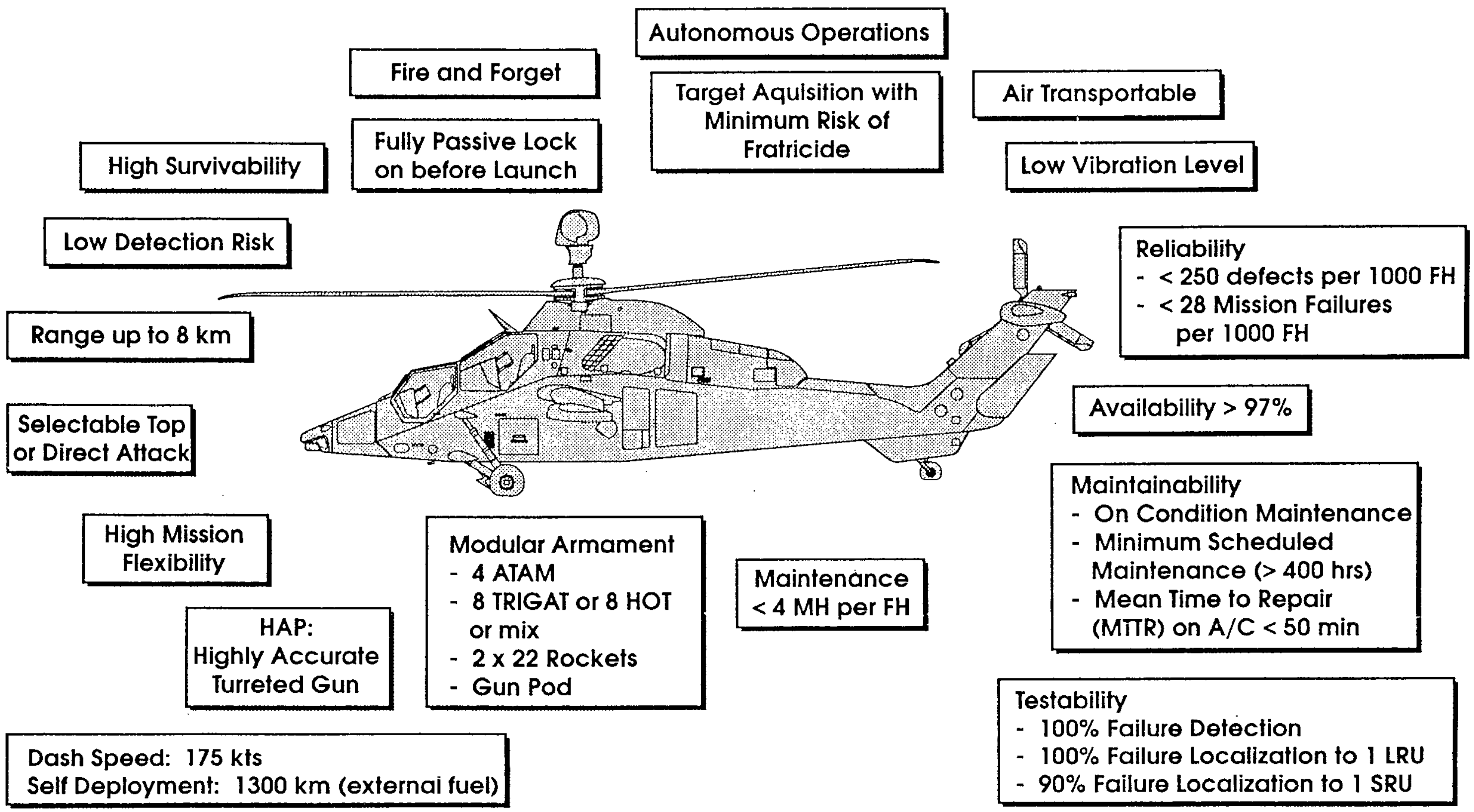


Fig. 4.-4: Military effectiveness, operations and support

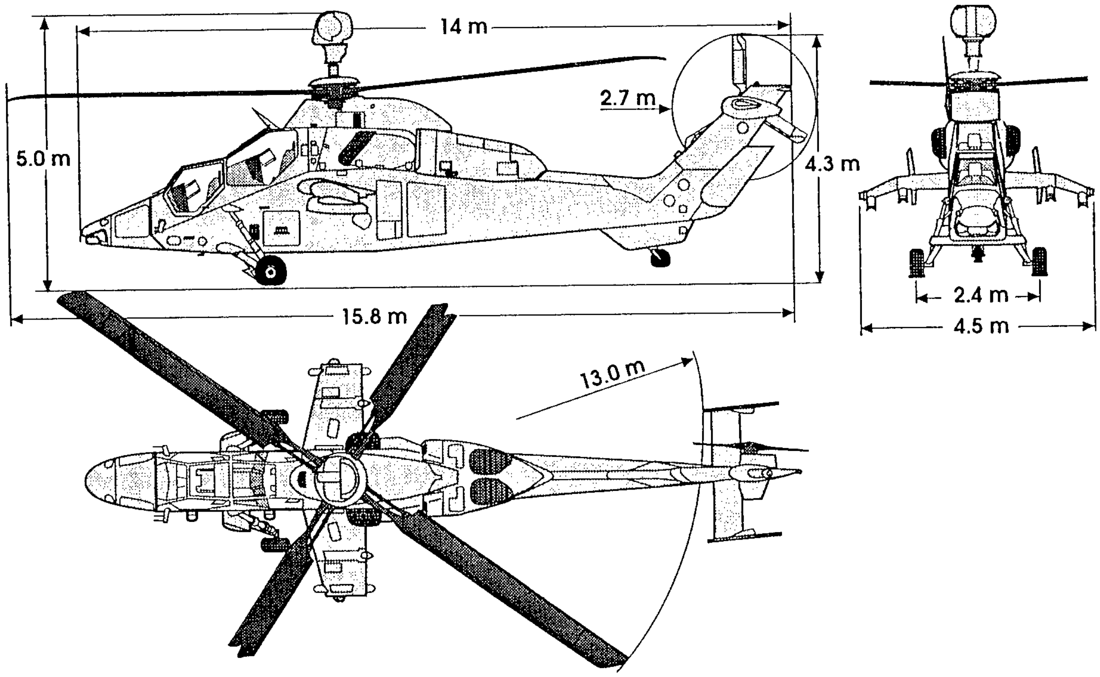


Fig. 5.1-1: Main dimensions

TIGER KEY DESIGN FEATURES

Design optimized for anti-tank/combat support missions

DYNAMIC SYSTEM

- Main Rotor:
  high agility hingeless, composite/ elastomeric bearings, 4-bladed, diameter = 13.0 m
- Tail Rotor:
  3-bladed, diameter = 2.7 m
- Engine:
  MTU/Turbomeca/Rolls-Royce MTR390, Power = 2 × 958 kW, APU-mode capability with one engine

FUSELAGE/AIRFRAME

- Tandem-seat configuration, cockpit-slope = 21°
- narrow silhouette composite fuselage
- modular equipment compartments, Arinc 600 concept
- 90% Mil Std 1290 crashworthiness

LANDING GEAR

- fixed, track = 2.4 m

FLIGHT CONTROL SYSTEM

- mechanical primary controls
- duplex digital AFCS

AVIONICS

- common basic avionics system
- dedicated mission equipment packages
- system architecture based upon redundant Mil Std 1553B bus system using ADA HOL
- strap down autonomous navigation
- GPS back-up
- 4 × 6.25" MFD's/2 CDU's
- redundant electrical system

SIGHT AND COMPUTER SYSTEMS FOR AUTONOMOUS OPERATION

Fig. 5.1-2: Key design features

	UHT/HAC	HAP
Hover out-of-ground effect	3250 m	3250 m
Vertical rate of climb	5.3 m/s	5.3 m/s
Max. rate of climb	10.7 m/s	11.0 m/s
Armed config. flight speed	146 kt	150 kt
Cruise speed 1)	118 kt	126 kt
Design limit speed	161 kt	174 kt
Max. range, internal fuel 1)	670 km	725 km
Design mission endurance	2 h 50 min.	2 h 50 min.
Max. endurance, internal fuel 1)	3 h	3 h
Agility: yaw angle after 1 sec.	40°	40°
Max. air-air missiles range	> 5 km	> 5 km
Max. autonomous identification ..... and engagement	5 km	5 km
Max. internal fuel	1080 kg	1080 kg
Max. fuel (int. & ext.)	1575 kg	1575 kg

Design take-off weight: 5400 kg / 1) Alternative gross weight: 5800 kg
All performance are given at sea level, ISA conditions, at design take off weight except 1);
the UHU/HAC configuration encompasses 8 HOT and 4 STINGER and the HAP configuration a gun and 4 Mistral

Fig. 5.2-1: Main performance

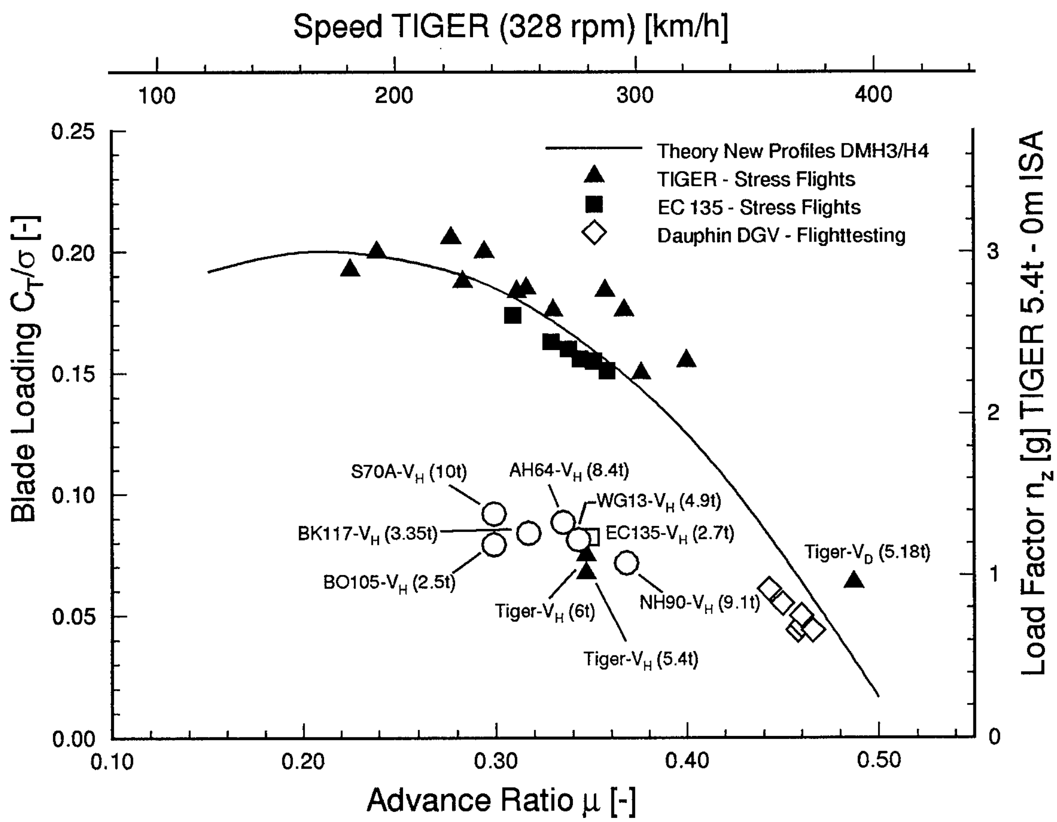


Fig. 5.2-2: Load factor - speed capability

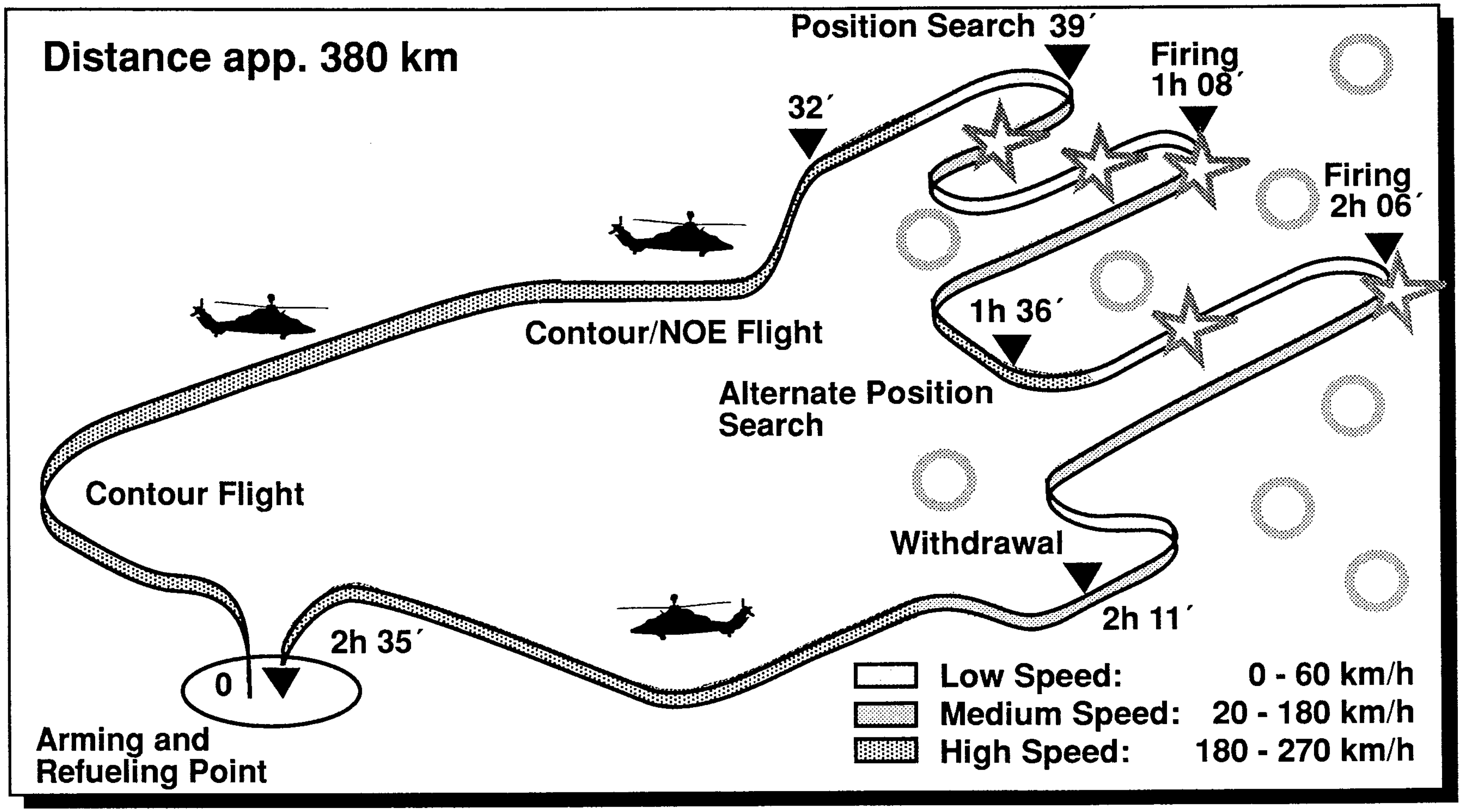


Fig. 5.2-3: Example mission profile - UHT combat support/day

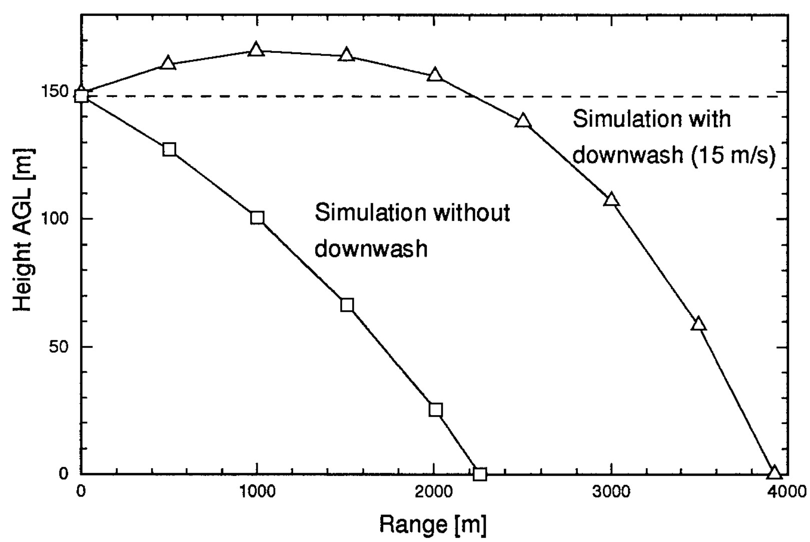


Fig. 6.1.1-1: Influence of main rotor downwash on the flight path of rockets (simulation)

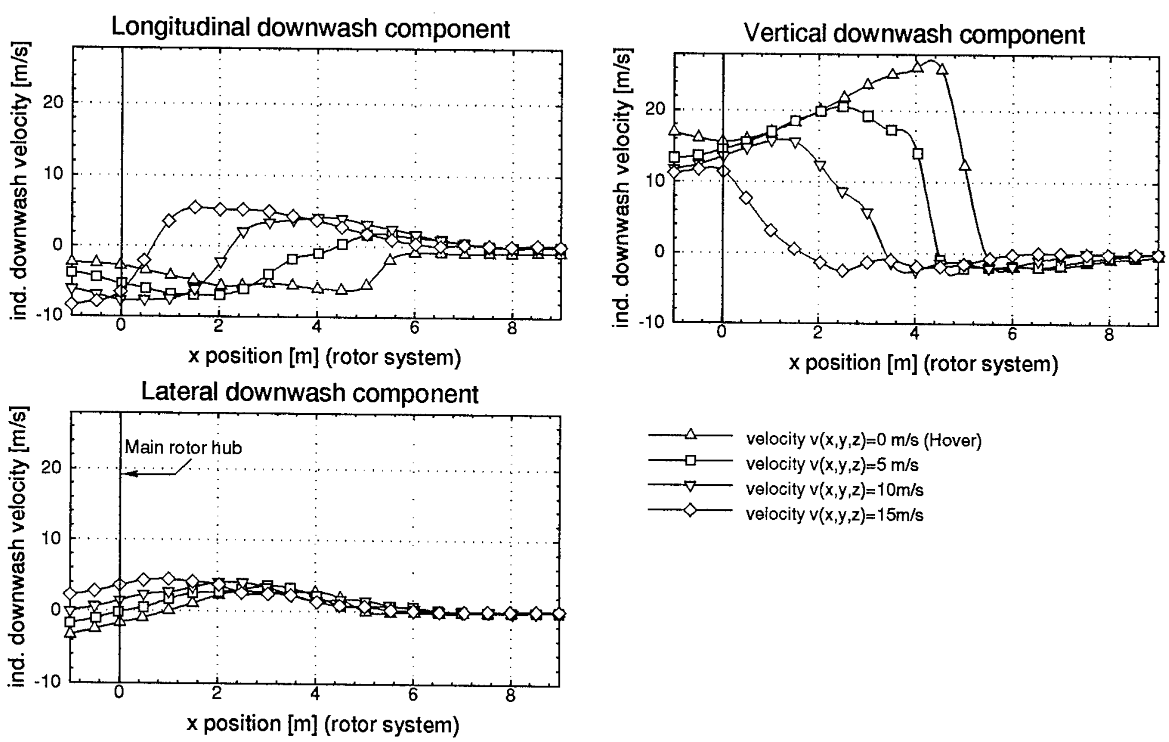


Fig. 6.1.1-2: Downwash velocities beneath the main rotor (z=-2 m, y=2 m relative M/R hub)

	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5
Project Status	initial aft	initial half aft	initial fwd	DAUPHIN aft	final production type
Span [m]	3.42	1.71	3.42	2.6	2.4
Chord [m]	0.75	0.75	0.75	0.56	0.54
Area [m^2]	2.56	1.28	2.56	1.45	1.3
Rel. Area [%]	100	50	100	57	51
Aspect Ratio	4.56	2.28	4.56	4.66	4.44
Volume [m^3]	19.2	9.6	14.1	10.9	9.75
Airfoil	NASA GA(W)	NASA GA(W)	NASA GA(W)	--	NACA 63-415
Spoilers	NO	NO	NO	leading and trailing edge	leading and trailing edge
Setting [°]	8	8	8	7	1.5
Endplates Area [m^2]	0.75	0.75	0.75	0.67	0.75

Fig. 6.1.2-1: Tailplane configurations flight tested

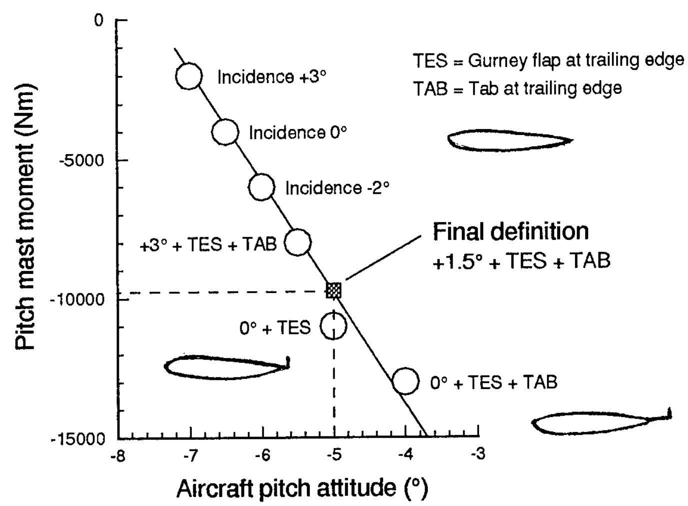


Fig. 6.1.2-2: Pitch attitude and mast moment trends for different settings and modifications of tailplane configuration

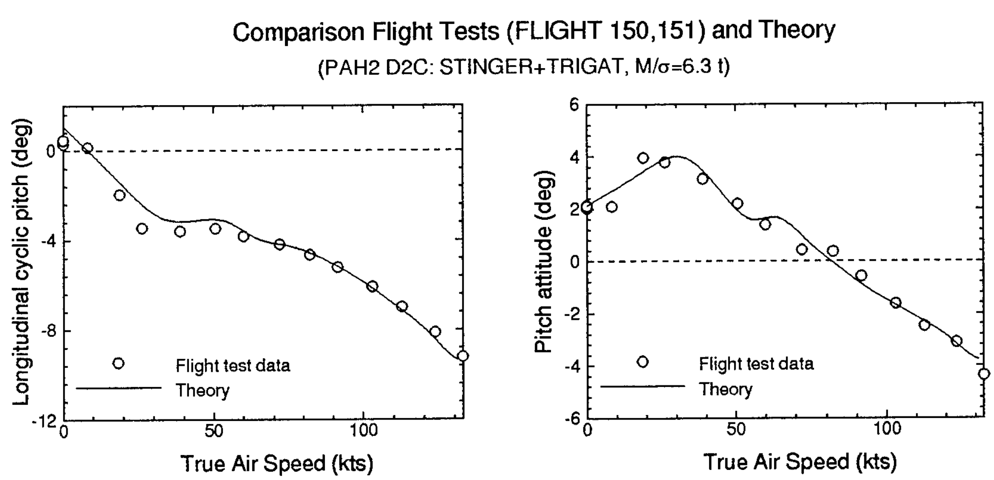
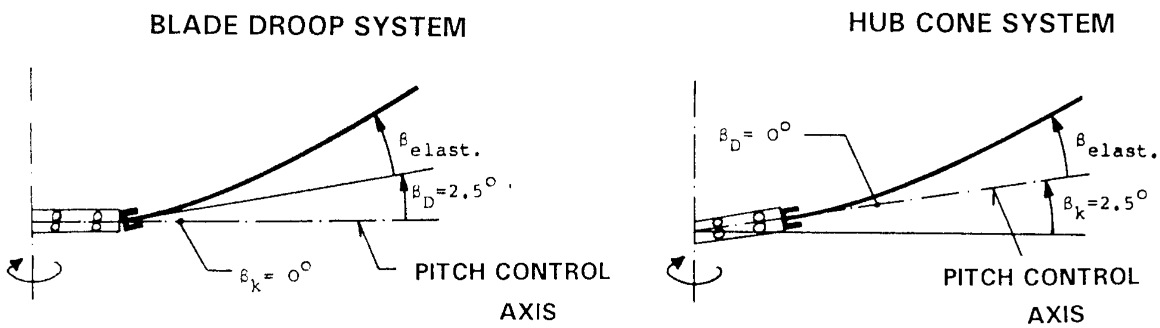


Fig. 6.1.2-3: Level flight trim situation



β_D = BLADE DROOP ANGLE

β_K = HUB CONING ANGLE

β_{elast} = ELASTIC BLADE FLAPPING

Fig. 6.1.3-1: Definitions of blade droop and hub coning angle

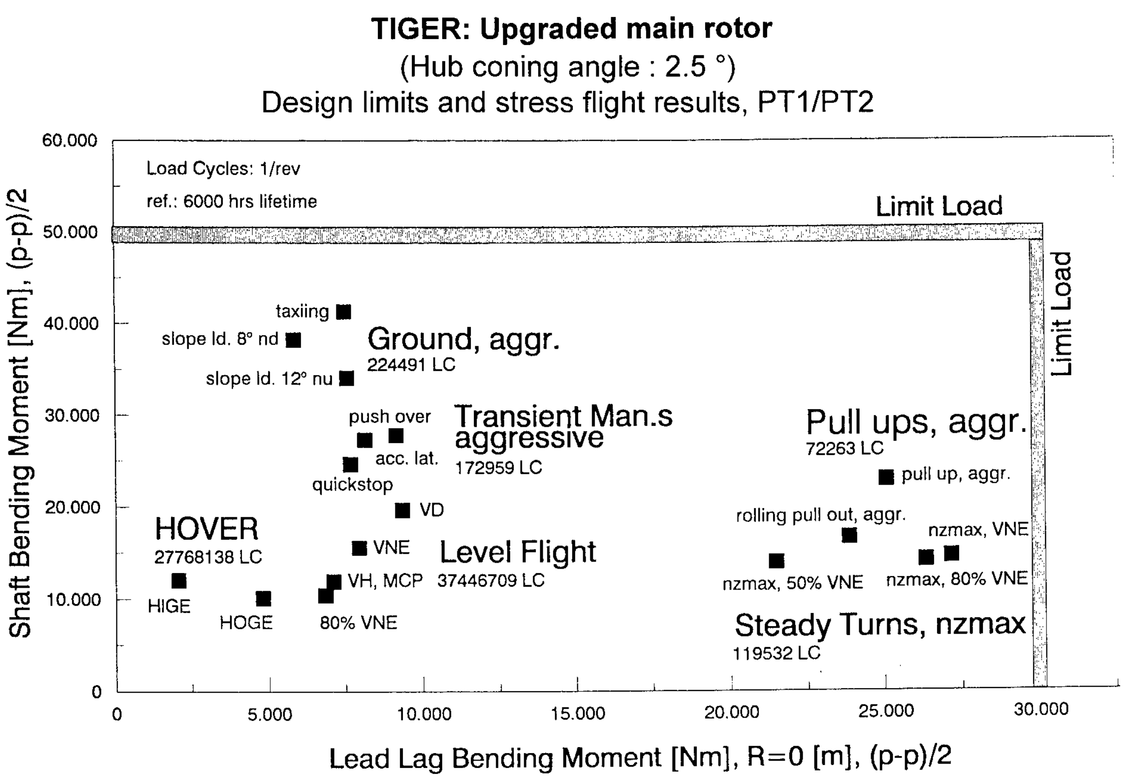
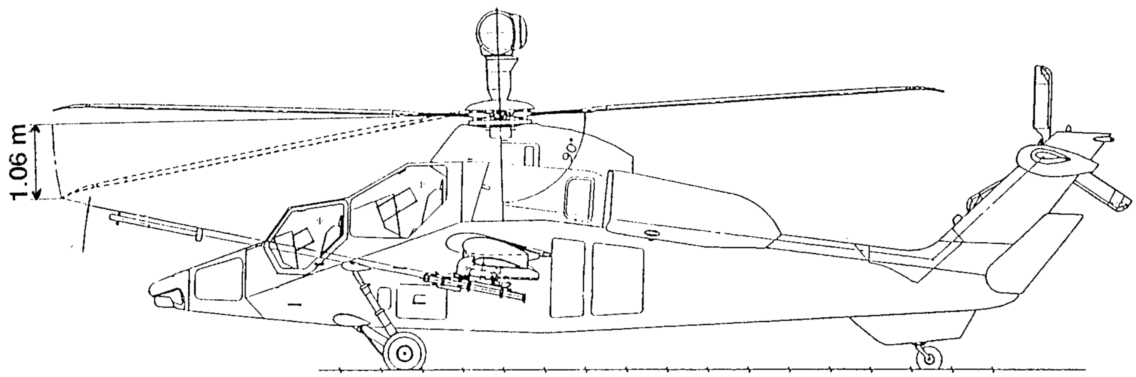


Fig. 6.1.3-2: Main rotor mast and blade lead-lag bending moment envelope



Case Nr.	Designation	Flapping Angle [°]	Max. Deflection [m] at r=6.5m (*)
0	Limit Load Flapping	-10.3	-1.06
1	Push-Over-1g (calculated)	-7.8	-0.79
2	Taxiing (Flight Test : PT1 F487)	-5.8	-0.6
3	Push-Over (Flight Test : PT1 F390)	-5.5	-0.55

* under Main Rotor Plane perpendicular to Rotor Mast

Fig. 6.1.4-1: Main rotor blade clearances to missile trajectories

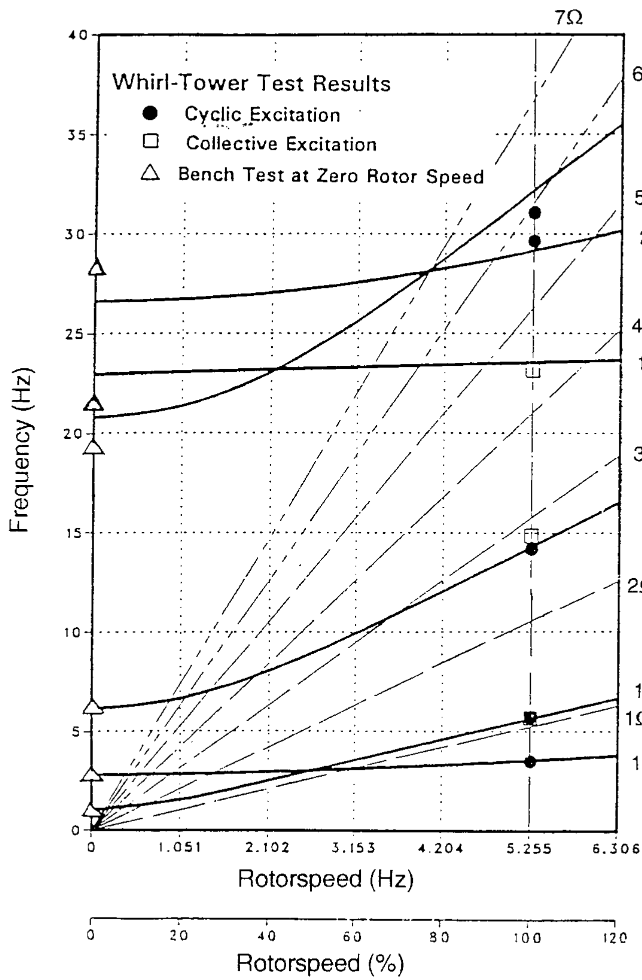
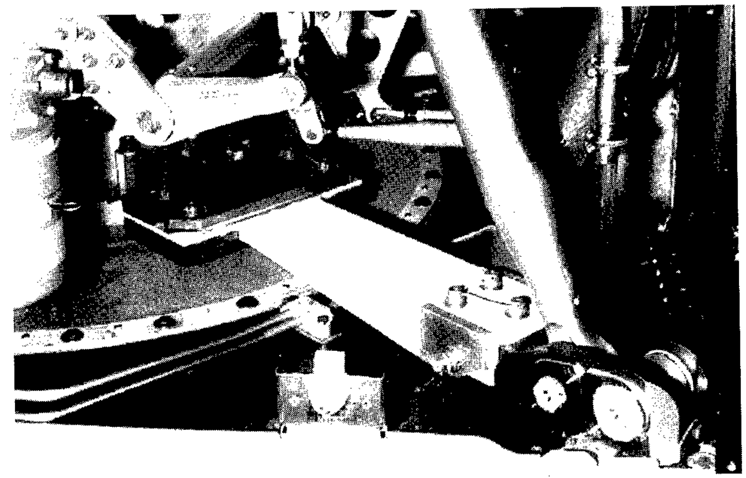


Fig.6.1.5-1: Main rotor frequency diagram



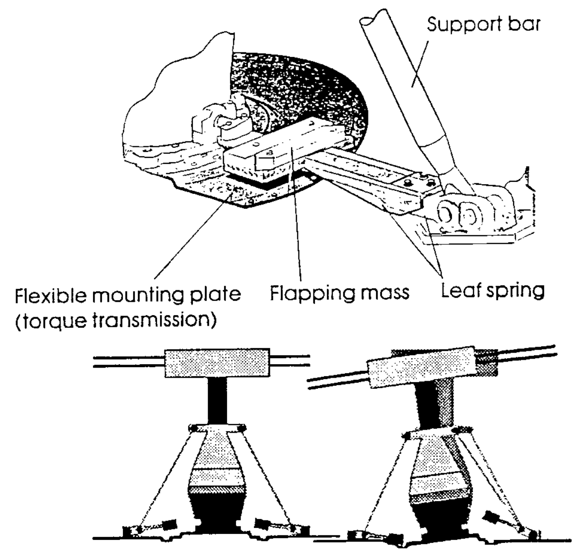


Fig. 6.1.5-2: SARIB anti-resonance system

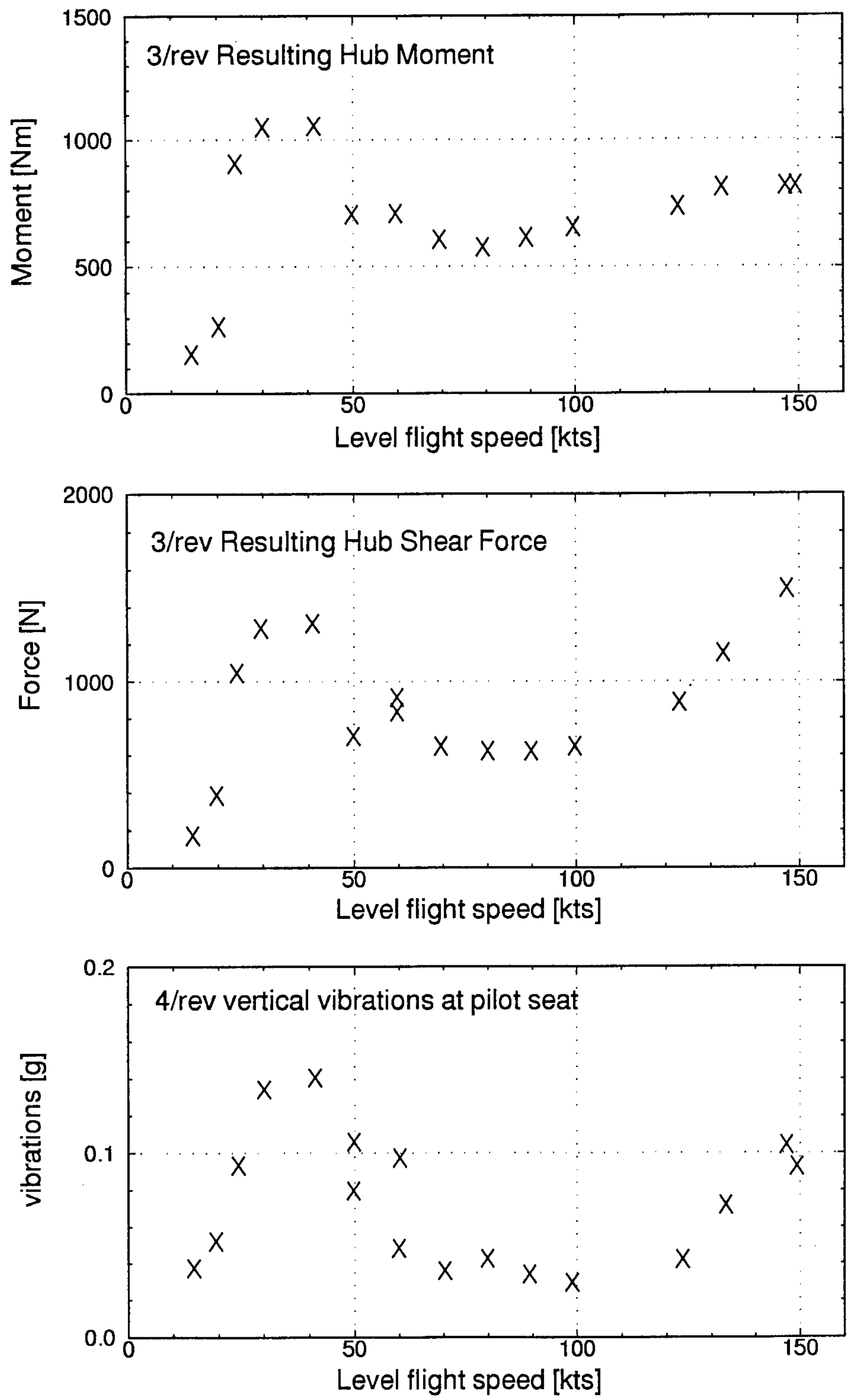


Fig. 6.1.5-3: Vibratory main rotor hubloads and related vertical vibrations at the pilot seat (flight test results PT1)

TIGER PT3-F206 - Mast mounted sight (V002) - Level flight lateral vibrations relative to TIGER specs.

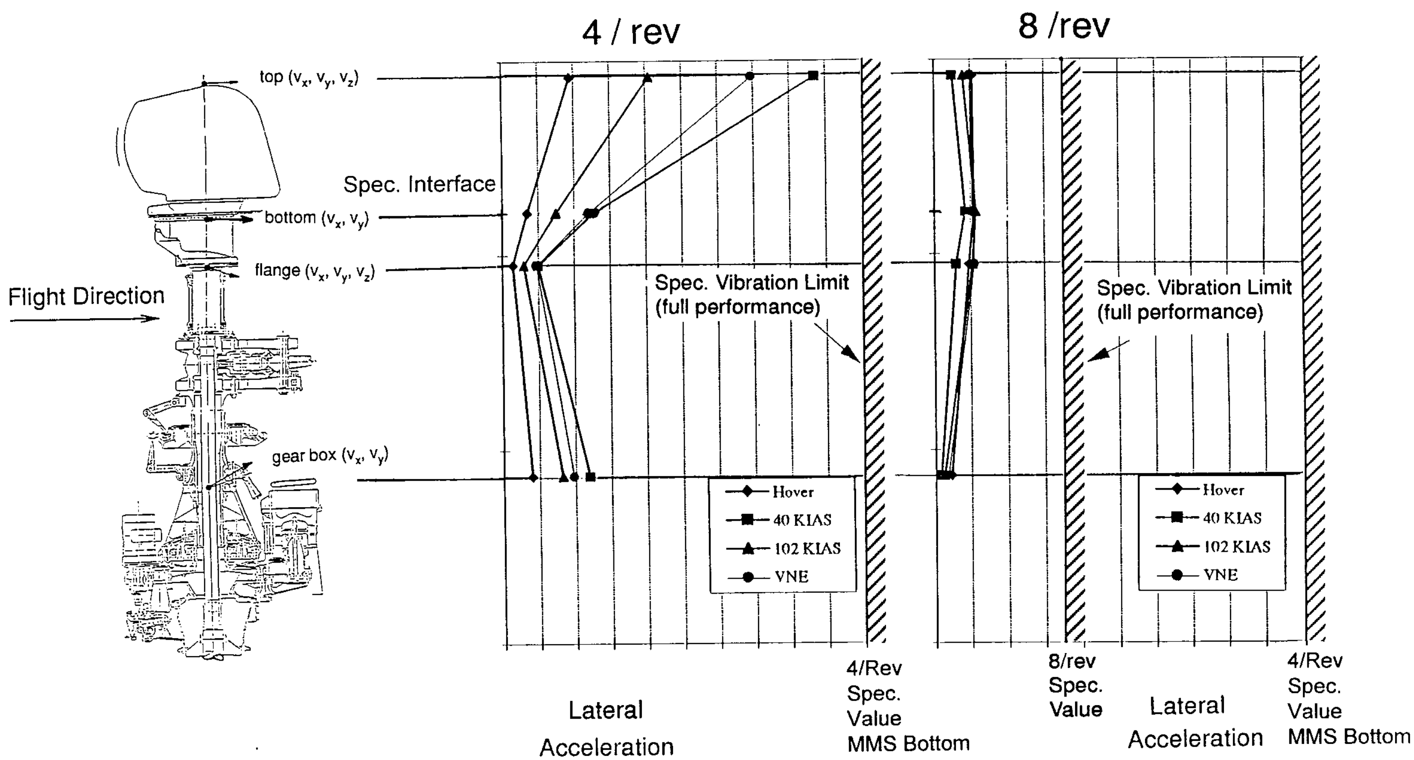


Fig. 6.1.5-4: Translatory accelerations at MGB, MMS complex in level flight

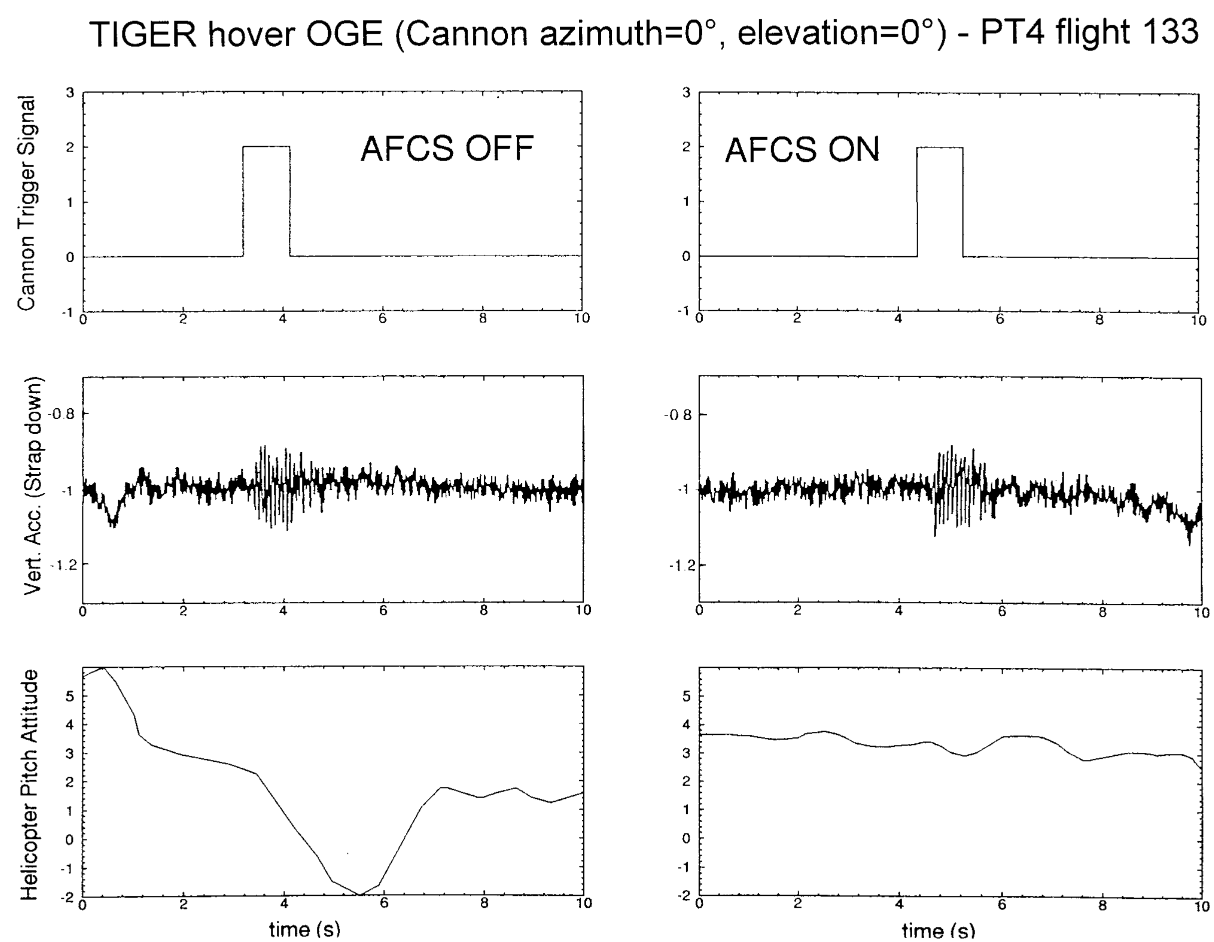


Fig. 6.1.6-1: Effectiveness of AFCS gun compensation on pitch attitude

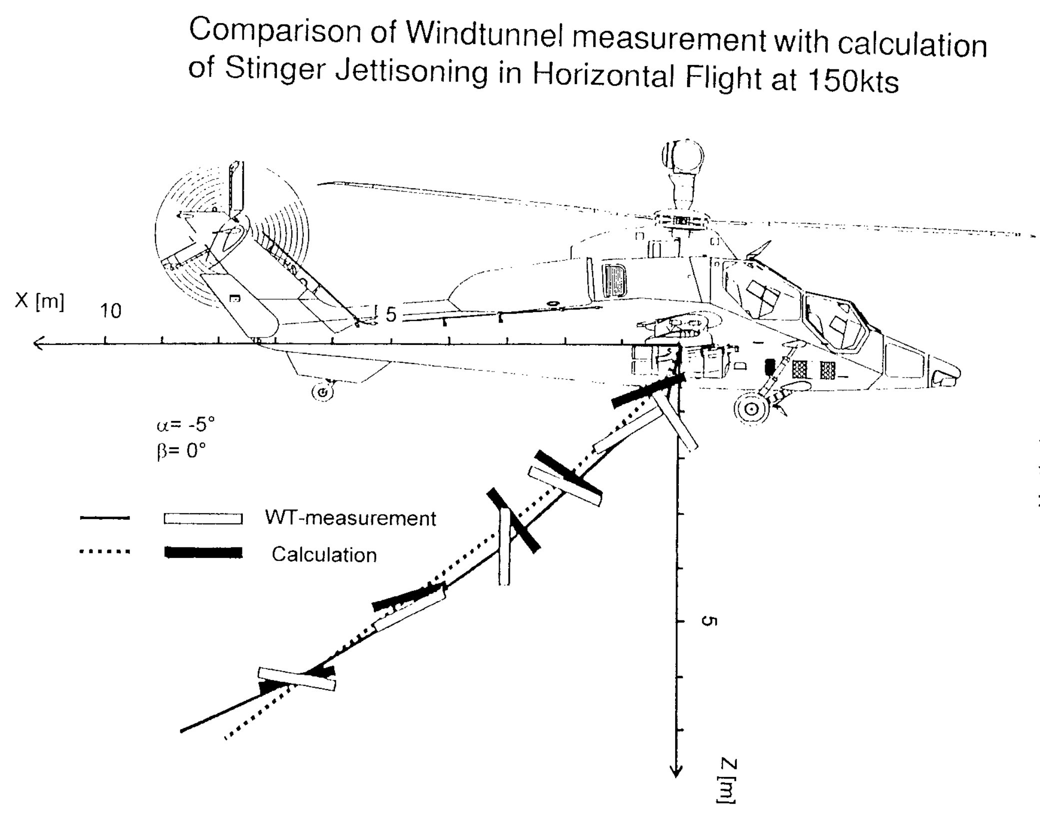


Fig. 6.1.7-1: Jettisoning simulation, comparison with windtunnel results STINGER (horizontal speed: 150 kts)

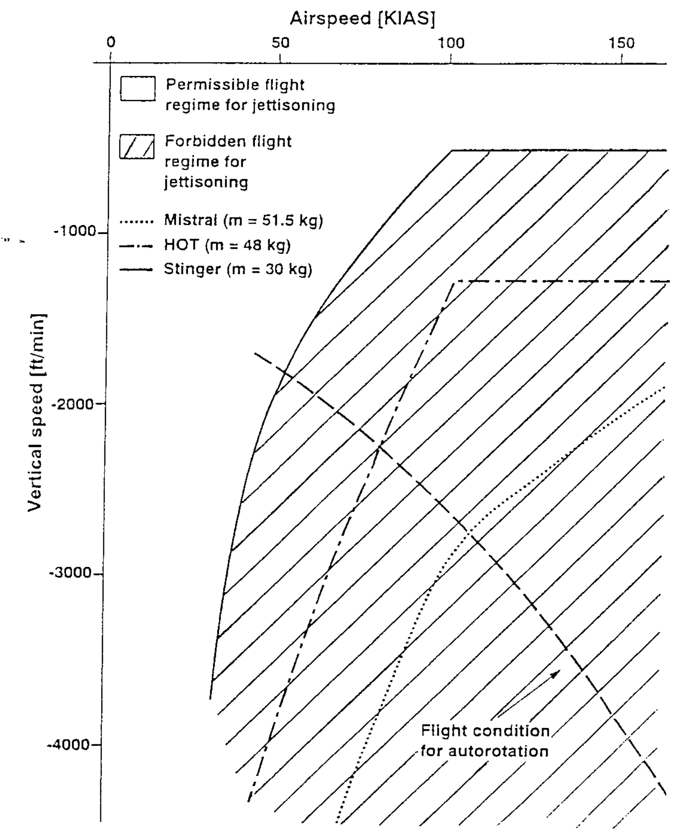


Fig. 6.1.7-2: Calculated STINGER, HOT, MISTRAL jettisoning flight envelope

TIGER WEAPON SYSTEM INTEGRATION FLYING TESTBEDS

- MTR 390 flying testbed PANTHER AS 565
  - MTR 390 engine and FADEC functional development testing
- ATA flying testbed PANTHER AS 565
  - Functional development testing of anti-tank armament TRIGAT launcher and OSIRIS mast mounted sight
- AVT flying testbed BK117
  - Functional development testing of digital map device (DKG) and HF radio data communications for UHT

TIGER WEAPON SYSTEM INTEGRATION GROUND TEST FACILITIES

- PIR/SIR primary/secondary integration rigs at ECD and ECF for avionics and mission equipment
  - Equipment/subsystem testing, functional chain testing, flight test support trouble shooting
- ANSIR
  - AFCS development and acceptance testing with navigation systems in the loop
- SIMCO
  - Cockpit simulator development of cockpit MMI functions

INTEGRATION AND QUALIFICATION OF WEAPON SYSTEM ON THE HELICOPTER

Status	Documentation	Purpose of test	Examples
B-Tests	B-Test specification	Test of wiring and black boxes (powered by external sources and by use of break-out boxes)	- Power supply tests - Signal tests - Harmonisation
C-Tests	C-Test specification	Functional checks over the complete „functional chain" (end to end)	- Initialisation - Functional checks with ammunition simulators
Integration and Developme nt tests	Ground- and flight test orders	- Investigation of environment - Functional check system of system under real conditions - Check of performances	- Temperature, vibration, EMC - MMI Aspects - Functional behaviour in complete operational envelope (weapon separation, angular velocities) - Aiming accuracy, hit probability, combat range, loading-unloading
Qualificatio n and Acceptance tests	Qualification test program (with Q/T parameters specification requests, related test programs)	Official proof that the complete weapon system meets the requirements inside the operational envelope	- Integration - Target aquisition - Slug-firing

Fig. 6.2-1: Outline of TIGER weapon system integration effort

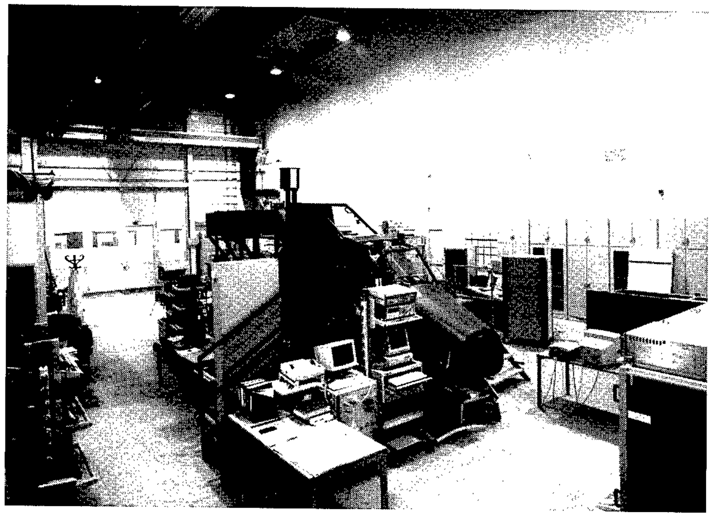


Fig 6.2-2: PIR - Primary integration rig for avionics and mission equipment (UHT MEP) at ECD

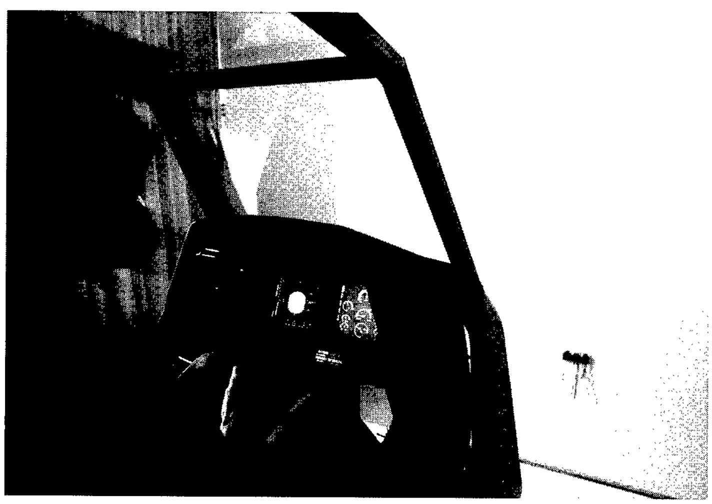


Fig. 6.2-3: SIMCO - Cockpit simulator for MMI functions development at ECD

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Structural analysis	Helicopters (EH-101)
External stores	Helicopters (Tiger)

14. Abstract

This publication includes the papers presented in a NATO Advisory Group for Aerospace Research and Development (AGARD) Lecture Series. This Lecture Series considered the problems of integrating externally mounted weapons on helicopters. The focus is on aeromechanical and structural aspects, with additional discussion on operational issues. It addresses new aspects in the field of helicopter/weapon system integration; it places a strong emphasis on the lessons learned from recent experiences in actual development programs. The publication includes case histories of weapons integration on the AH-64 Apache, the RAH-66 Comanche, the EH-101, and the Tiger.

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